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Maneuverable penetration system for horizontal exploration in soft ground [pt.1]

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MANEUVERABLE PENETRATION SYSTEM
FOR HORIZONTAL EXPLORATION IN SOFT GROUND

[pt.1]

Alan William Katz

[ρt. 1]

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FOR HORIZONTAL EXPLORATION IN SOFT GROUND

by

ALAN WILLIAM KATZ
SB, United States Naval Academy
(1970)

Submitted in partial fulfillment

of the requirements for the degree of

Master of Science in Civil Engineering

at the

Massachusetts Institute of Technology
June 1975

Signature of Author .. *Alan W. Katz* . . . . . .
 Department of Civil Engineering, May 9, 1975

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 Chairman, Departmental Committee on
 Graduate Students of the Department
 of Civil Engineering

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ABSTRACT

MANEUVERABLE PENETRATION SYSTEM
FOR HORIZONTAL EXPLORATION IN SOFT GROUND

by

ALAN WILLIAM KATZ

Submitted to the Department of Civil Engineering
on May 9, 1975, in partial fulfillment of the
requirements for the degree of Master of Science
in Civil Engineering.

Horizontal directionally controlled
drilling in soft ground is a relatively
unexplored frontier in the realm of
earth drilling. Therefore, the informa-
tion source force for this subject is a
select group of men, who are associated
with the petroleum, coal and pipeline
industries.

The first step in the investigation was
to establish the state of the art for
horizontal directionally controlled
drilling in soft ground. Then several
companies, who are developing direc-
tional drilling equipment, were
contacted. Four basic maneuverable
penetration systems(MPS) were then pre-
liminarily designed from available com-
ponents. The penetration devices differ
principally in the manner in which the
normal force at the drill bit is devel-
oped. In the mandrel system, normal
force is developed by pushing a non-
rotating steel drill pipe from the sur-
face, whereas in the thrust applicator
system the normal force is developed by
thrusting against side-wall anchor pads.

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These two basic MPS's were then related
to the following four general geological
conditions which might be found in an
urban area within the United States:
(1) loose sand or soft clay; (2) dense
sand or stiff clay; (3) residual soil;
and (4) any one of these conditions in
combination with subsurface utility
lines. The four MPS models (2 mandrel
and 2 thrust applicator) were then
analyzed with dimentionless parameters to
determine the suitability of each system
to a specified geological environment.

Finally, several factors, some unique to
horizontal directionally controlled
drilling, were considered in detail in
the design of the four soft ground
maneuverable penetration systems. These
include: the anchor pad and deflection
shoe bearing capacity; required soil
strength for thruster operation; fric-
tional force effects on the drill pipe
and thruster cable; drill path and exit
angle limitations; drilling fluid char-
acteristics; and the radius of curva-
ture of the drill bit.

Thesis Supervisor: Charles H. Dowding

Title: Assistant Professor in Civil Engineering

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ACKNOWLEDGMENT

I would like to express my deepest appreciation to Professor Charles H. Dowding, my thesis advisor, for the many hours of precious time he willingly contributed to provide guidance, insight, and encouragement toward the formulation of this thesis. The successful completion of this thesis is a testimony of his dedication to helping his students gain the utmost from their time at MIT.

I would also like to express my sincere thanks to Mr. Myron Emery, formerly of Titan Contractors, whose willingness to share with me his vast wealth of knowledge and experience in directional drilling has been the keynote in developing this topic, while his patience in answering my questions is truly a valuable gift he retains. I am also deeply indebted to Mr. Emery for the guidance he provided in contacting various individuals associated with the oilwell drilling industry.

I want to thank the following men who were kind enough to freely and extensively contribute their time, knowledge, and experience, in their specialty

"Commit your work to the LORD, and your plans
will be established, Proverbs 16:3"

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CHAPTER 1

INTRODUCTION

1.1   OBJECTIVES

To design a maneuverable boring system for
horizontal exploration in a soft ground environment,
a few questions must be posed. Is there an available
mechanical system (i.e. one that can be assembled
from existing and tested components) that can be
maneuvered from the surface to explore soil conditions
along a proposed tunnel route? Can such a system
endure the effects of drilling in a sand-clay
environment below the water table? Are there any in-
hole thruster systems that can be operated in soft
ground and what are their limitations? If a boulder
or other subsurface obstacle is sensed ahead of the
device, can the excavation system be directionally
controlled to avoid this object? These are only a
few of the questions which will be addressed in
designing a horizontal boring system.

The multi-objectives of this study are to
establish the present state of the art in horizontal
directional drilling in a soft ground environment.

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Some of the unique problems associated with this type
of drilling will be discussed in detail. Then, in an
attempt to classify each system with its optimal
operating conditions, four basic urban geologies
which one might encounter while exploring horizon-
tally, will be considered with each potential
Maneuverable Penetration System(MPS). Finally, by
comparing each system, using a dimensionless analysis
technique and individual system compatibility
drawings, the various MPS's will be ranked according
to each of the four geologies.

1.2   SCOPE OF STUDY

In order to better understand exactly what
parameters this study will include, it will be bene-
ficial to define and specify the pertinent equipment
terminology, assumptions, and unique vocabulary
associated with horizontal directional drilling.
A more complete list of the terms and symbols
associated with this study can be found in Appendix A.
A horizontal, directionally controlled boring in soft
ground is one in which an excavation device (motor
and bit), propulsion device (drill pipe or thrust
applicator), and a directional control device (bent
sub, articulated sub or deflection shoe) are combined
into one system in order to enter the earth's crust
at a predetermined angle; follow a predetermined

directional path to a desired depth; drill horizontally for a particular distance, making necessary course changes, and then maneuvering in such a manner that another inclined path is followed to penetrate upward to the surface. The resulting exit point is at a different location from the entry point.

Soft ground will be defined as a soil condition in which the unconfined compressive strength (q_u) ranges from 0.25 tsf(29.96 kN/m^2) to 4.0 tsf(383.3 kN/m^2). The former unconfined strength normally is for loose sands and soft clays while the latter is associated with dense sands or heavily overconsolidated clays.

All of the equipment included, as recommended mechanical systems in the conclusion of this study, are "on-shelf" items. On-shelf means the equipment or technical knowledge is readily available, with little or no modification or development, to be combined with existing devices.

Two basic mechanical excavation systems will be examined: the mandrel system and the thrust applicator system. A mandrel system is one which requires the use of drill pipe, and special surface equipment which applies a normal force to the drill pipe and consequently to the drill bit. The thrust applicator

system is one which employs an in-hole thrusting device which anchors against the bore-hole walls, providing the required normal force on the drill bit for penetration. Both the thrust applicator and the mandrel system will include an on-board electronic navigation and geological sensing package.

The size of the bore-hole considered will be in a range from 4-1/2 in(11.4 cm) up to 12 in(30.5 cm) in diameter with a desired horizontal distance of 5000 ft(1525 m), and a desired maximum depth below the ground surface of 500 ft(152.5 m). With these bore-hole limitations in mind, the optimal MPS must be flexible enough to meet the above requirements. In addition, the MPS should be able to maneuver around a 5-10 ft(1.53-3.05 m) diameter object if encountered on the directionally drilled path.

The emphasis of this study is not to review and analyze every possible means of directionally drilling a horizontal hole, but instead, to consider only those devices which are in the on-shelf category. For example, there are numerous thrust applicators, but only one was in the prototype stage and being actively tested in a geological environment.

Another unique aspect of this study is the relative novelty of horizontal directionally controlled boring for small diameter holes. Consequently, there

does not exist an extensive bibliography in order to establish a basis for investigation. Therefore, most of the information gathered for this study is from letter communications, phone calls and personal visits. This naturally limits one's level of information, thereby becoming dependent upon the industry's or researcher's willingness to divulge their personal knowledge or experience. In an attempt to deal with this problem, both practical experience and previously established technical methods of analysis have been combined to evaluate the various design choices.

It is also worthwhile to state that due to a system design approach of the excavation, propulsion, and directional control as one system, the level of detail in any one area within each subsystem has been limited within the main body of the report and is covered in slightly more detail in the appendices. The reader must realize that an in-depth study can be accomplished on almost any one area covered by this report.

At the onset of this study the thrust applicator MPS was only conceptual in nature. In the preliminary investigation, it was found that a thrust applicator did in fact exist and was being tested. In addition, several other alternative systems are in

the developmental stage as discussed in Chapter 2.
As more information was collected, it became obvious
that at the present state of the art, some of the
equipment was applicable to one type of geology
while a completely different geology required a
different system. Therefore, four urban subsurface
environments were adopted for comparison of the
various systems. These are: (1) soft clay
(low S_u/σ_v) and poorly graded loose sands (low D_r);
(2) heavily overconsolidated clays (high S_u/σ_v) or
uniform dense sand (high D_r); (3) a residual soil
which includes boulders and possible pinnacles; and
(4) any of the previous soil conditions in combination
with the presence of subsurface man-made objects.

In order to satisfy the on-shelf equipment and
technology requirement, the writer had to pursue an
industry that was actively involved in drilling
directional holes in the earth--the oil well industry.
Therefore much of the information in this report is
the result of an effort to apply and convert oil well
drilling technology and experience into familiar
civil engineering, geotechnical terminology.
This then presents directionally controlled horizon-
tal drilling from a different perspective than
drilling out ahead of a large diameter tunnel boring
machine. A few of the differences being the amount

of space available, the location of the directional
control panel and the techniques used to control the
direction of the drill bit.

This thesis is organized such that Chapter 2
presents the state of the art for mechanical devices
as applied to horizontal directionally controlled
drilling. Several of the important considerations
and unique problems associated with drilling
horizontally in soft ground will be addressed in
Chapter 3. In Chapter 4, the results of this study
are summarized with the aid of a dimensionless
analysis scheme. In an attempt to make the chapters
more readable, detailed formulas and calculations,
and in-depth coverage of the subject matter are
contained within the appendices.

CHAPTER 2

STATE OF THE ART
FOR HORIZONTAL DRILLING EQUIPMENT

2.1   INTRODUCTION

Describing the current status of horizontal directionally controlled drilling as an art is very appropriate. The actual drilling is an art in which only a relatively few individuals in the United States know or have had extensive experience with. As a result of the uniqueness of this particular type of earth drilling, much of the information gathered for this section has been done so by telephone conversations, letters, and personal visits. The references at the end of this chapter are given so that the reader can contact the persons related to specific areas of interest.

This state of the art section will deal mainly with the present on-shelf equipment and techniques which are currently being applied or have on-shelf potential for application in soft ground horizontal long hole boring. For an initial listing of all possible current and novel drilling techniques

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applicable to both soft ground and hard rock horizontal holes, the reader is encouraged to pursue the report entitled, <u>Improved Subsurface Investigation for Highway Tunnel Design and Construction</u>, May, 1974 by Fennix and Scisson, Incorporated. This particular state of the art section will begin where the previously mentioned report concluded.

The purpose of this section is to present an overview of the existing and potential mechanical devices available for horizontal directionally controlled drilling. Detailed drawings, pictures, and specifications of this equipment can be found in Appendices C and D.

Four major areas of the maneuverable penetration system will be discussed: (1) downhole motors, (2) downhole thrust applicators, (3) directional control equipment and techniques, and (4) drill bits. In an attempt to orient the reader, Figures 2.1 and 2.2 are simple schematic drawings of the mandrel and thrust applicator systems, respectively.

2.2   DOWNHOLE MOTORS

<u>Dyna-Drill</u> This is a positive displacement hydraulic motor which operates on the principle of a Moyno pump in reverse as shown in Figure 2.3. The motor has only one external moving part, the bit and bit sub.
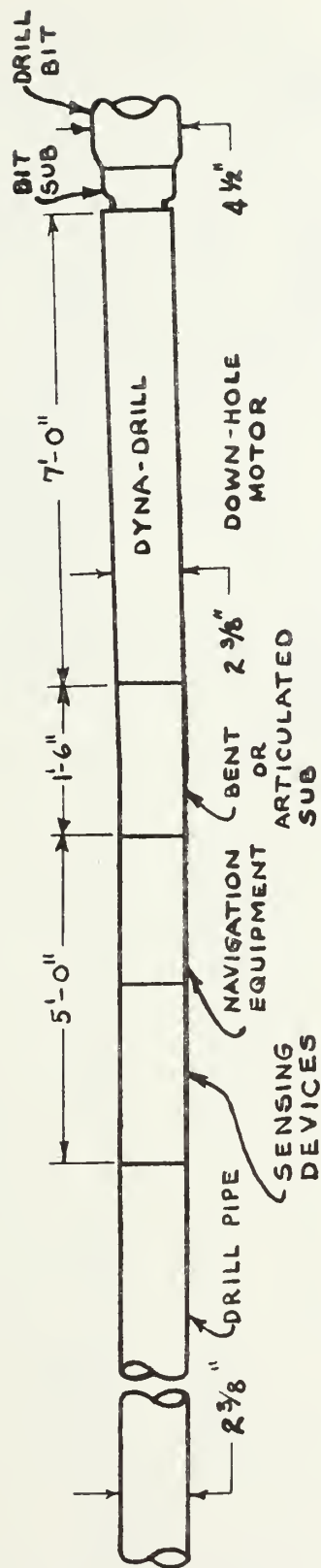
NOT TO SCALE:

FIGURE 2.1 Schematic of Mandrel MPS

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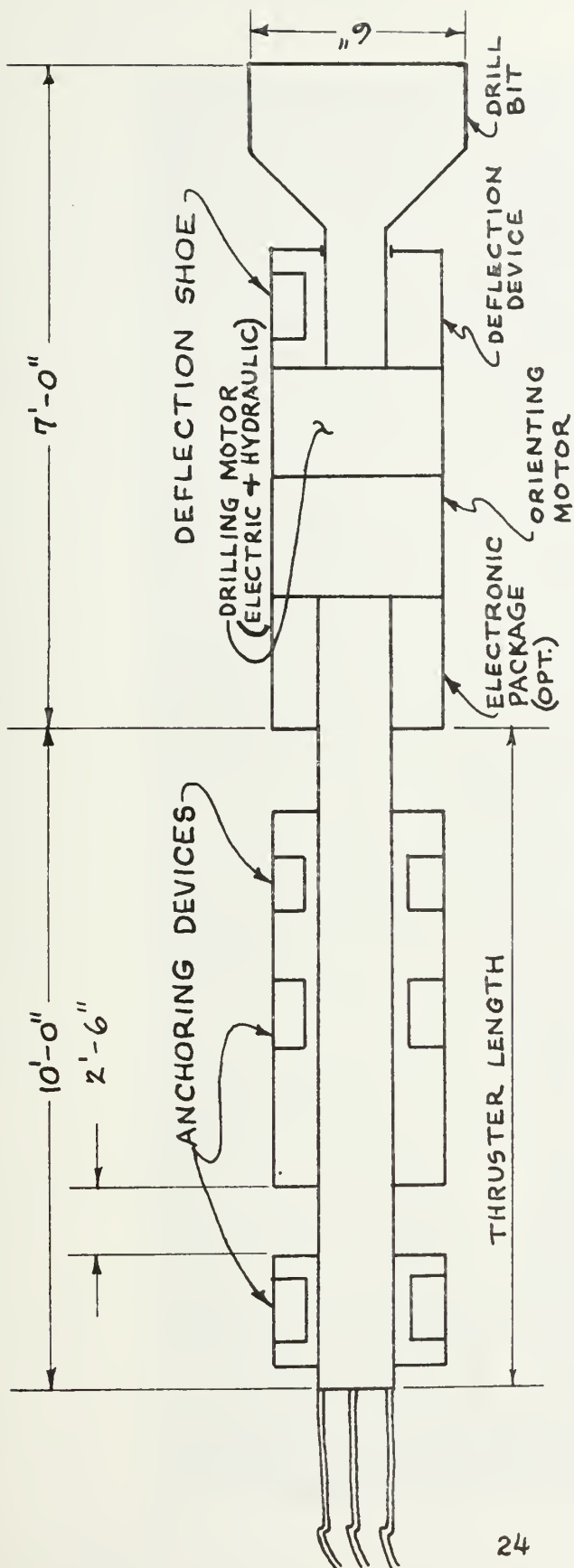
FIGURE 2.2 Schematic of Thrust Applicator MPS

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1 Dump Valve Assembly
2 Multi-Stage Motor
3 Connecting Rod
4 Bearing and Drive Shaft Assembly
5 Rotating Bit Sub
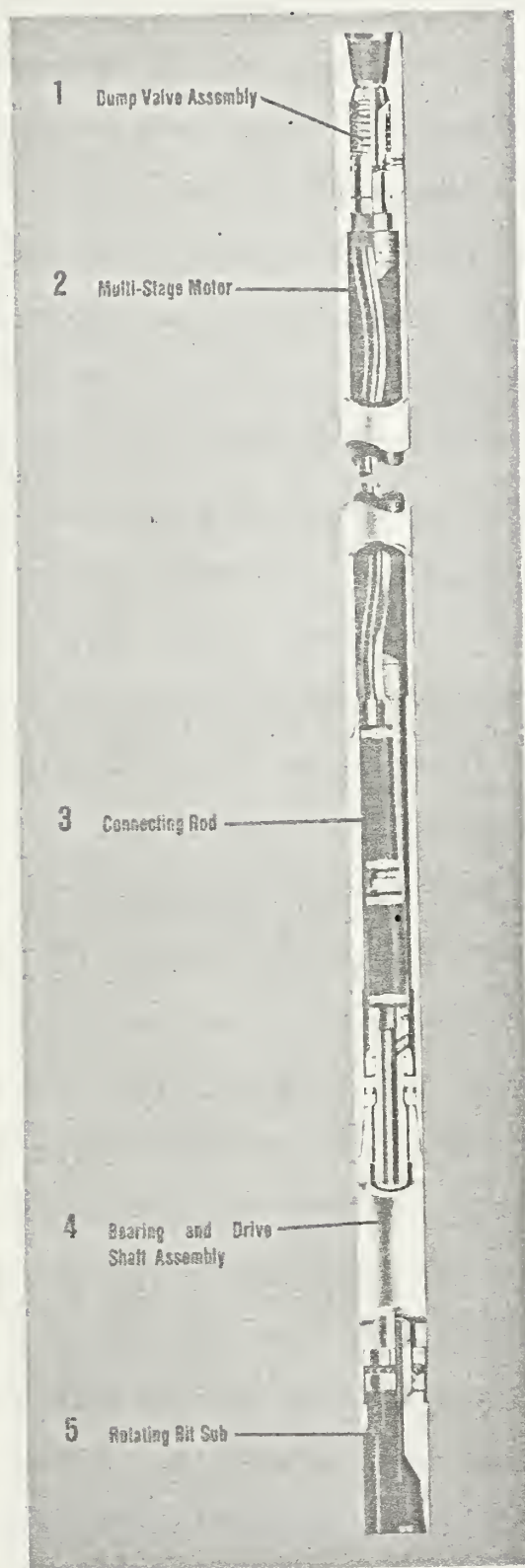
FIGURE 2.3   Dyna-Drill Cross-section (after Dyna-Drill)

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Since the pumped drilling fluid passes between the
stator housing and the rotor which in turn rotates
the bit, there does exist the requirement to rotate
the drill pipe. Several advantages are gained from a
stationary drill pipe, especially in directional
drilling, which will be further discussed in
Chapter 3. The application of Dyna-Drill most
relevant to horizontal penetration has been the
1-3/4 in(4.45 cm) O.D. downhole motor used in
drilling pilot holes for underground pipelines
beneath rivers. As a result of the experience gained
from these river crossings, Dyna-Drill has designed
a 2-3/8 in(6.03 cm) O.D. downhole motor which will
produce the same torque output, flow rate, and
required drop in hydraulic pressure across the motor
as the 1-3/4 in(4.45 cm) O.D. motor (Tschirky, 1975).
The 2-3/8 in(6.03 cm) model will be approximately
7 ft(2.13 m) long and will have the capability of
boring a 4-1/2 in(11.43 cm) hole. This particular
Dyna-Drill will be an optimal motor for horizontal
drilling because of its relative maneuverability,
lightness in weight, and low fluid flow requirements.
The 2-3/8 in(6.03 cm) O.D. motor is still in the
developmental and testing stage but even from its
conception it was thought of and designed for

horizontal drilling applications. Currently
Dyna-Drill is the most utilized downhole directional
motor in the oil industry today.

Turbo-Drill A turbo-drill is a multi-stage axial,
mud turbine, downhole motor illustrated in Figure 2.4
and is used for straight and directional drilling.
Each stage of the motor consists of a rotor which is
attached to the axial shaft and a fixed stator se-
cured to the housing. A typical 5 in(12.7 cm)
turbo-drill will contain 86 of these stages in line
(Eastman, 1969). The fluid velocity loss across the
turbine will determine the torque and the horsepower
output. To date, the shortest length turbo-drill
downhole motor is 17.4 ft(5.3 m) with a 5 in(12.7 cm)
O.D. and weighs approximately 750 lb(340 kg).
This motor has not been used for horizontal direc-
tional drilling to date and in fact, does not appear
to be suited for this particular type of drilling.

Hydraulic Drill Motor A newly developed downhole
motor is an internal gear driven, positive displace-
ment pump operating in reverse as a motor.
The particular pump, which has been field tested as
a motor, was built by the W. H. Nichols Company in
Waltham, Massachusetts as a special order for
Continental Oil Company for drilling in soft coal.

Item No.	Description
1	Top Sub....... ....
2	Shaft Cap........................
3	Lockwasher-Turbine Section........
4	Stator Spacer.....................
5	Shaft Key-Turbine Section..........
6	Intermediate Bearing Body..........
7	Intermediate Bearing Sleeve.........
8	Stator................. ....
9	Rotor.........................
10	Turbine Housing ....
11	Turbine Shaft........ ....
12	Internal Collar.....................
17	Lockwasher-Bearing Section.........
18	Flow Ring................ .....
19	Spacer-Bearing Section.............
20	Shaft Key-Bearing Section .. ..
21	Thrust Bearing Sleeve...... ..... .
22	Thrust Bearing Body................
23	Thrust Disc.....................
24	Thrust Bearing Spacer...... ......
25	Lower Bearing Body................
26	Lower Bearing Sleeve...............
28	Bearing Housing........ ....
29	Lower Sub Lock Ring..............
30	Lower Sub.....................
31	Bearing Shaft ....
32	Lower Bearing Spacer.............
33	Retaining Ring....... ....
34	Catch Ring........ . ...
36	Spline Clutch Box..................
37	Clutch Wear Pins...... ....
38	Clutch Spacer.....................
39	Spline Clutch Pin Sub..............
40	Float Retainer Ring.................
41	Shaft Coupling................ ...
42	Assembly "O" Ring ....
43	Stator Screen....... ....
44	Lift Sub.....................
45	Shaft Cap Lock Screw.......... .....
46	Baker Float*...... ....

DIRECTIONAL
INTEGRAL
TURBODRILL

FIGURE 2.4   Turbine Drill Cross-section (After Eastman, 1969)

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The basic element of this motor is a gerotor as shown
in Figure 2.5. The gerotor consists of an eccentric
locator-ring, an outer rotor, and an inner rotor
which is attached to the shaft. These gerotors are
placed in series depending on the desired maximum
flow rate. A mud drilling slurry or water, flowing
at a rate of 30 gpm(0.114 m^3/min) through a 16 stage
motor will produce 10 horsepower at 300 RPM
(Coffey, 1975). The maximum size hole drilled with
this motor has been 6 in(15.24 cm) in diameter.
Overall length of this current model is 4 ft(1.22 m)
with an outside diameter (O.D.) of 5 in(12.7 cm).
Therefore, it is very well suited for directional
drilling in soft ground.

Electric Motor An electric drilling motor, available
as an on-shelf item from Century Electric Motor
Company, has also successfully drilled 6 in(12.7 cm)
diameter horizontal holes in soft coal seams for the
Continental Oil Company (Dahl, 1975). A standard
submergible motor was coupled, through a reduction
gear box, to a drill bit. The motor is
3-11/16 in(9.37 cm) O.D. with a length of
32-7/16 in(81.84 cm) requiring 460 volts at
10.0 amps (full load) to produce 5 horsepower output
(DeGrand, 1975). The electric motor may improve
horizontal drilling capabilities because of its short

PIN STOP
IN HOUSING

REVERSING RING   OUTER ROTOR   INNER ROTOR
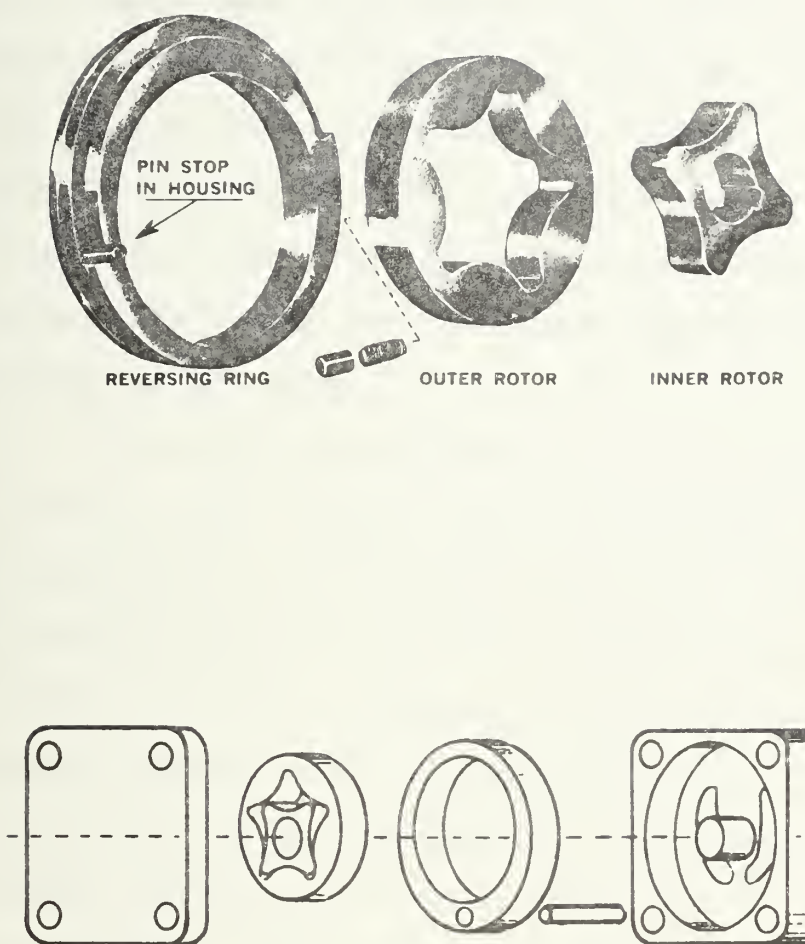
FIGURE 2.5 Gerotor (After Nichols)

length, competitive horsepower rating and the low
energy requirements. The motor does require cooling,
but the minimum requirements of 5 GPM(0.32 l/sec)
can be easily satisfied since a higher flow rate will
be required for the removal of cuttings.
The drilling fluid, which acts also as a cooling
fluid, is routed through an annulus between an outer
protective casing and the smaller diameter outer
casing of the motor.

There are a few problems associated with the use
of this motor. First, there always exist the
possibility of a failure by electrical shorting
below the water table and by an overload failure as a
result of the bit jamming in a hard formation.
Another unique problem associated with the electrical
motor is the reduction gear box which is necessary to
reduce the high motor RPM's to the low bit RPM
requirement. This reduction gear box has a tendency
to have a relatively short service life.

In the overall viewpoint, the motor is smooth
running, efficient, and is compatable with systems
in use for horizontal drilling in soft ground.

2.3   DOWNHOLE THRUST APPLICATORS
Drilco Thrust Applicators DRILCO, Division of Smith
International, Incorporated in Midland, Texas has

built and supplied to the Continental Oil Company, a
hole-wall anchored thrust applicator. This thrust
applicator supplies an in-hole bit normal force and
has the ability to move the motor and bit both for-
ward and reverse directions. Figure 2.6 illustrates
an artist's conception of the entire system.

To date, several thousand feet of drilling have been
accomplished in soft coal with the longest continu-
ous hole being 1000 ft(310 m) long. Continental Oil
Company is currently testing and developing this
device in order to reach a goal of drilling more than
2000 ft(620 m) horizontally (Dahl, 1975). The force
applicator presently has two sizes: 2-3/4 in(7 cm)
O.D. by 7.6 ft(2.3m) long with an 18 in(45.7 cm)
stroke for a 3-1/8 in(8 cm) diameter hole which is
illustrated in Figure 2.7; and a 5-3/4 in(14.6 cm) by
10.6 ft(3.23 m) long with a 30 in(76.2 cm) stroke for
a 6 in(15 cm) diameter hole (Kellner, 1974).

The latter thruster size has been the most successful
to date in soft coal formations. The thrust appli-
cator has the capability to load and advance any type
of drilling motor in any direction. The unit can
also be backed out of the hole under its own power.
Directional control is gained through the use of a
deflection shoe located near the bit as shown in
Figure 2.2. The deflection shoe will be more

DRILCO INDUSTRIAL
Division of Smith International, Inc.

OMNI-DIRECTIONAL DRILLING SYSTEM

POWER-PACKAGE, HOSE TRANSPORTER, AND LAUNCHER

DYMA-DRILL

DRILL BIT MOTOR

ADVANCING/RETRACTING DEVICE

FIGURE 2.6 DRILCO Thrust Applicator System

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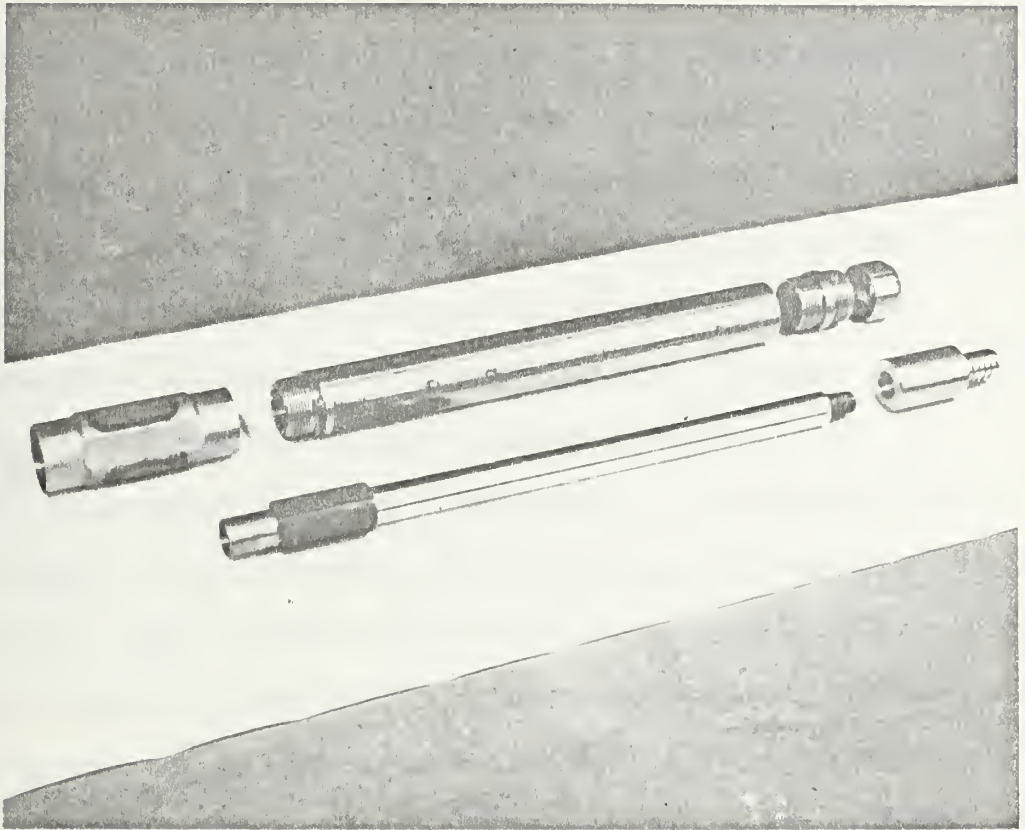
FIGURE 2.7 2-3/4 in. O.D. DRILCO Thrust Applicator
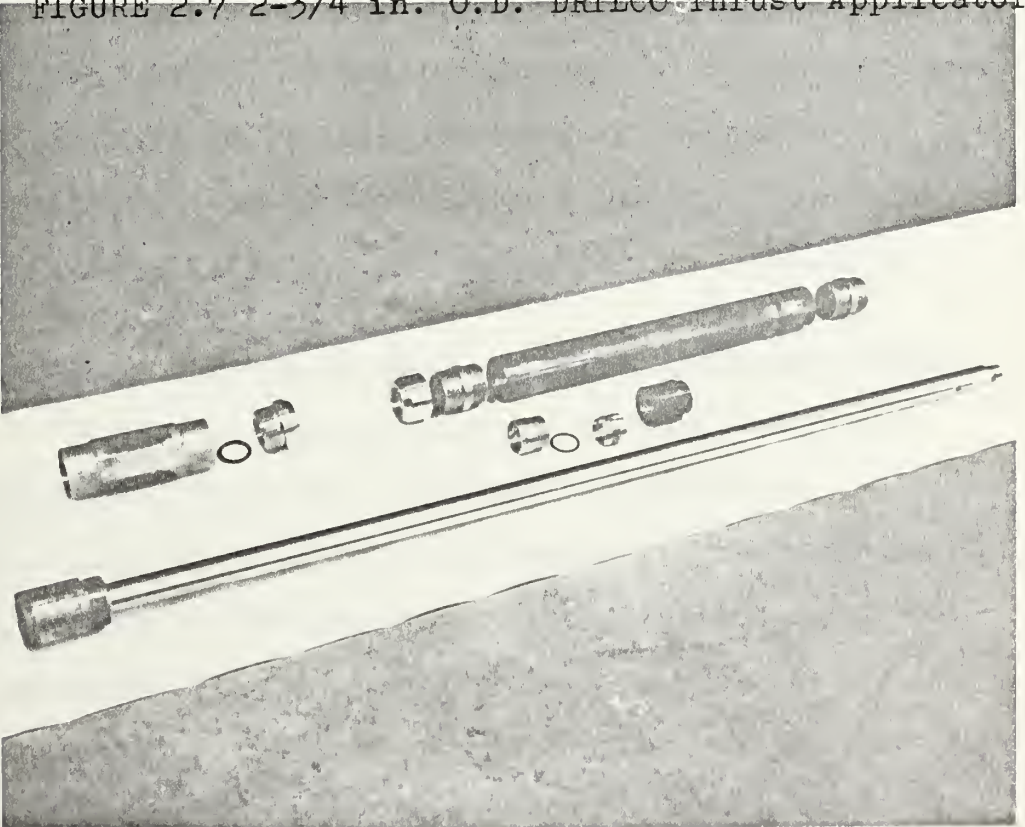
completely described in Section 2.4 of this chapter.
The DRILCO thrust applicator has successfully been
coupled with a Dyna-Drill, hydraulic motor, and an
electric motor. Other components attached to the
thrust applicator are an orientating motor and an
electronic package for navigation and sensing.
The thruster unit is hydraulically powered with a
downhole valving system, developed by Continental Oil
Company. This downhole valving system eliminates two
cables, thus leaving only one hydraulic cable for
powering the thruster, one for the necessary hydrau-
lics for the orientating motor and deflection shoe,
and one for the drilling fluid which can contain an
electric cable for the electronics equipment
(Edmond, 1975). Future developments will bring about
the compacting of this system even further by
reducing the number of external cables to two--one
for the drilling fluid and one for the hydraulics.

Newcastle University Root Analogue Tunneller (NURAT)

NURAT is a combination penetrator and thrust
applicator which was originally invented by
Dr. Daniel Hettiaratchi at the University of Newcastle
upon Tyne at Newcastle upon Tyne, England under the
auspices of the British Gas Corporation
(Hettiaratchi, 1974). Since conception, the British
Gas Corporation has taken over the development and

testing of this device (Spearman, 1974).

The author has communicated at length with both Dr. Hettiaratchi and Mr. Spearman from British Gas Corporation and because of their desire to protect pending patent applications on NURAT, they have released only limited information about the device. A schematic drawing from the University of Newcastle is shown in Figure 2.8.

NURAT was the result on several years of study by Dr. Hettiaratchi involving the mechanism by which roots grow in soil. When the pressure at the top of the root prohibits extension, the root expands radially outward hence stress relieving the area directly in front of the root tip which then allows the root to grow. This then is the reason for the device acquiring the name of "root analogue" tunneller.

The NURAT presently being developed by British Gas Corporation will be approximately 6 in(15.2 cm) in diameter with a length not exceeding 5 ft(1.5 m). The complete device should be light enough to be handled by two people. The power source will be a mobile hydraulic power pack which will provide the capability of reversing directions. The estimated penetration rate will be 60 ft/hr(18.3 m/hr) through clay or sand. No additional motor is required for this thruster because of its basic principle
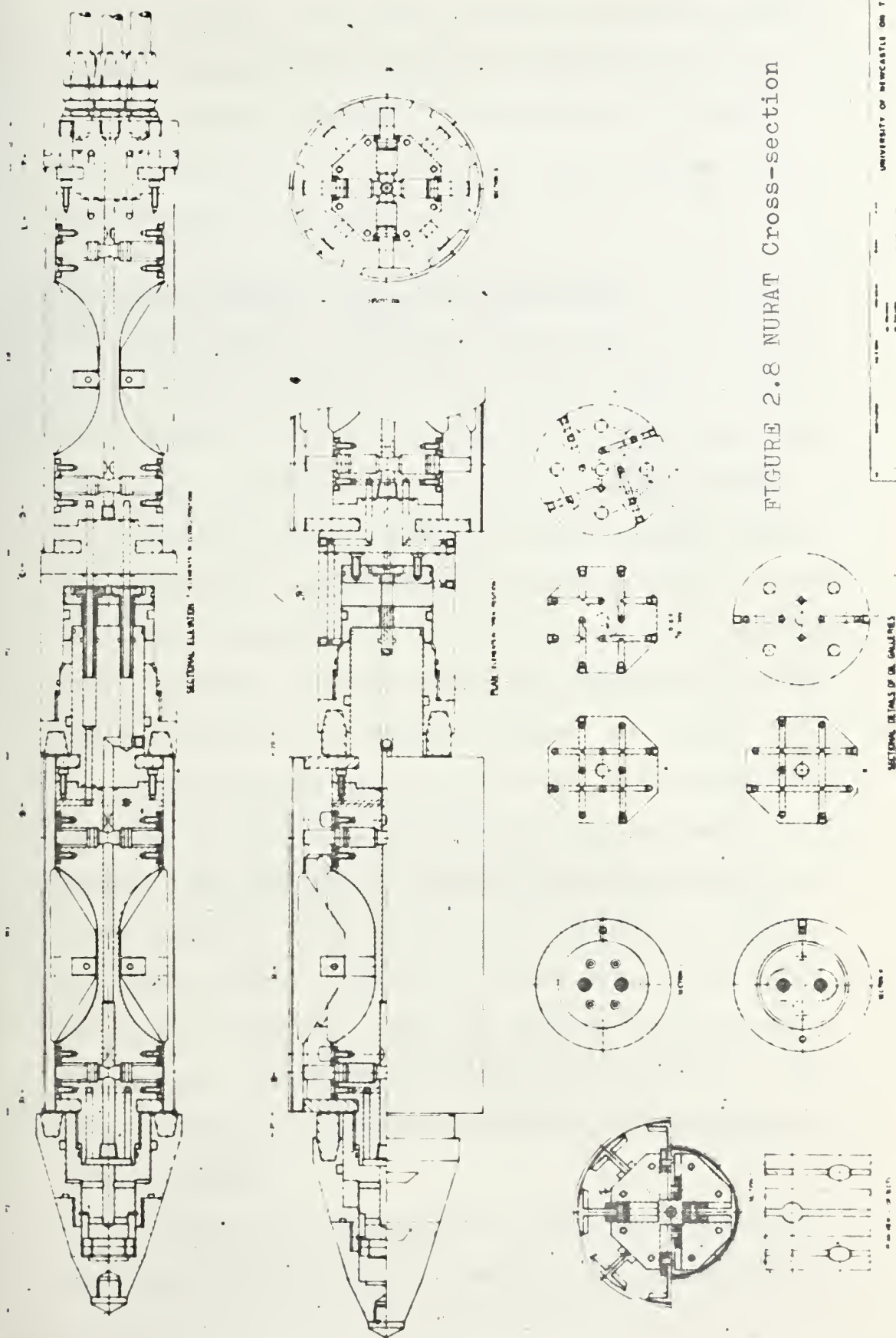
FIGURE 2.8 NURAT Cross-section

of penetration. One major problem area which must be resolved during the preliminary design phase is a suitable means to control the direction of NURAT. More information on this device should become available in the latter half of 1975.

British Government Post Office Ductmotor As a result of being unable to locate a device which would crawl down a pipe, the British Post Office designed their own ductmotor as shown in Figure 2.9. For this ductmotor, the following design criteria were imposed: the ductmotor had to be able to pass through water, mud, and silts, around bends and maneuver up and down inclines. In addition, it had to be able to operate over a distance of 1800 ft(549 m), pulling a coaxial cable without cable damage (Deadman and Slight, 1965).

The ductmotor has two air bags, one forward and one aft, connected by an extension arm as shown in Figure 2.9. The device has an inchworm motion such that, when the after air bag is inflated, securing the after section, the arm extends forward the distance of its stroke, then the forward bag inflates and secures itself to the tunnel wall while the after bag deflates and the arm contracts. This process is then repeated.

To date this ductmotor has only been used in cable and utility ducts. However, the principle
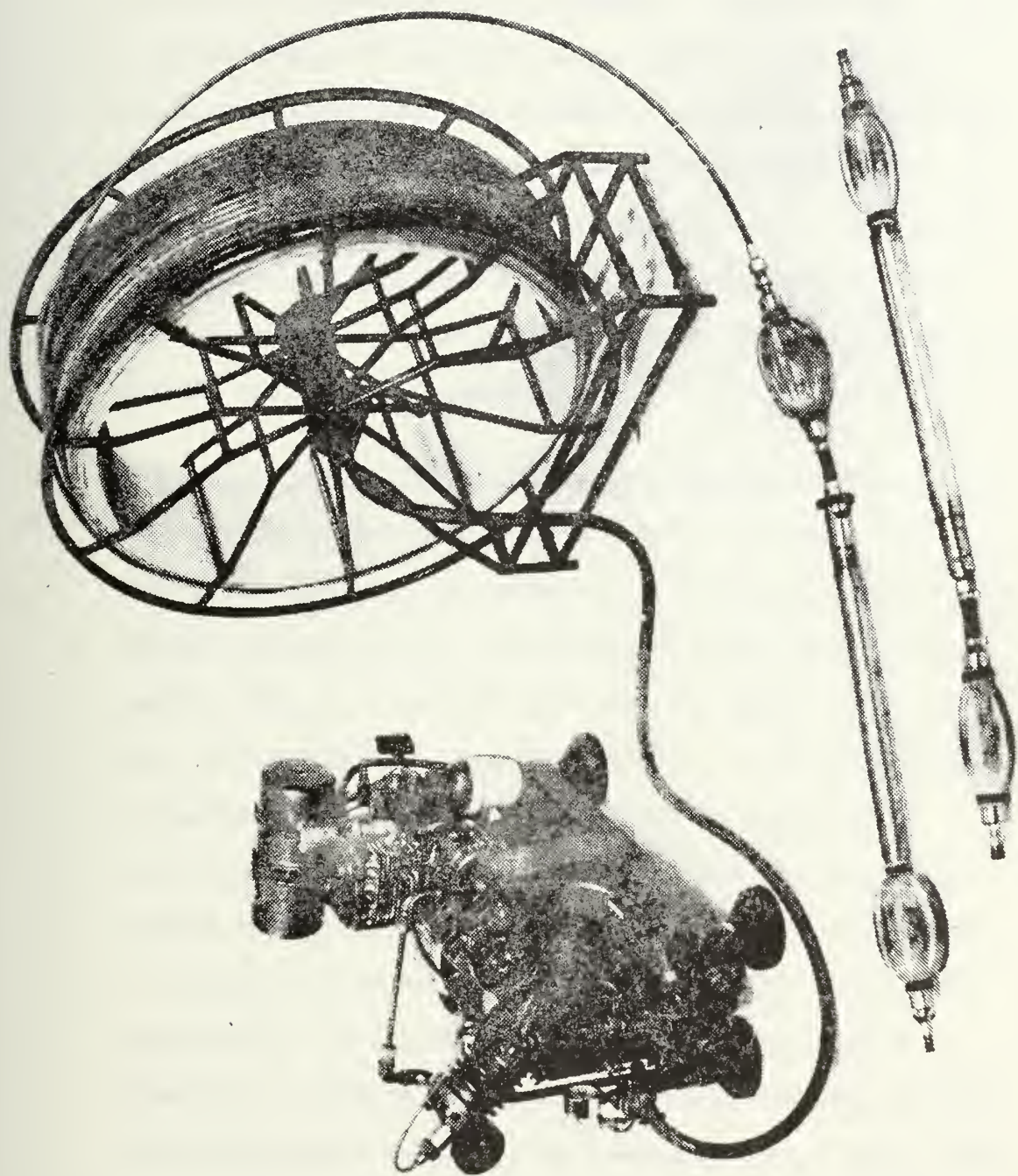
FIGURE 2.9 British Government Post Office Ductmotor

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of operation is similar to the previously described
DRILCO thrust applicator. The use of air bags for an
anchoring mechanism is a valuable concept while
penetrating soft ground, since tunnel wall distur-
bance would be greatly reduced. However, a provision
will have to incorporate a provision which would
enable the drilling fluid to return to the surface.
With some modifications, the ductmotor could have
the potential of being adapted as a thruster for soft
ground horizontal penetration.

U.S. Navy Polytoroidal Tunneling Thruster The Civil
Engineering Laboratory at the Naval Construction
Battalion Center, Port Hueneme, California has con-
ducted a feasibility study on the application of a
vermiculating tunneling thruster to horizontal dril-
ling (Williams and Gaberson, 1973). A vermiculating
or earthworm-like motion traverses a contacting
surface with a longitudal wave in the direction of
motion by cyclically expanding and contracting a set
of toroids as shown in Figure 2.10. The vermicula-
ting motion is controlled by a system of cyclic
timers in combination with a solenoid valving system.
This device was designed to penetrate in a rock, clay,
or sand medium using a cutting or boring device while
providing a firm base for high thrust as a result of
using a large contact surface.
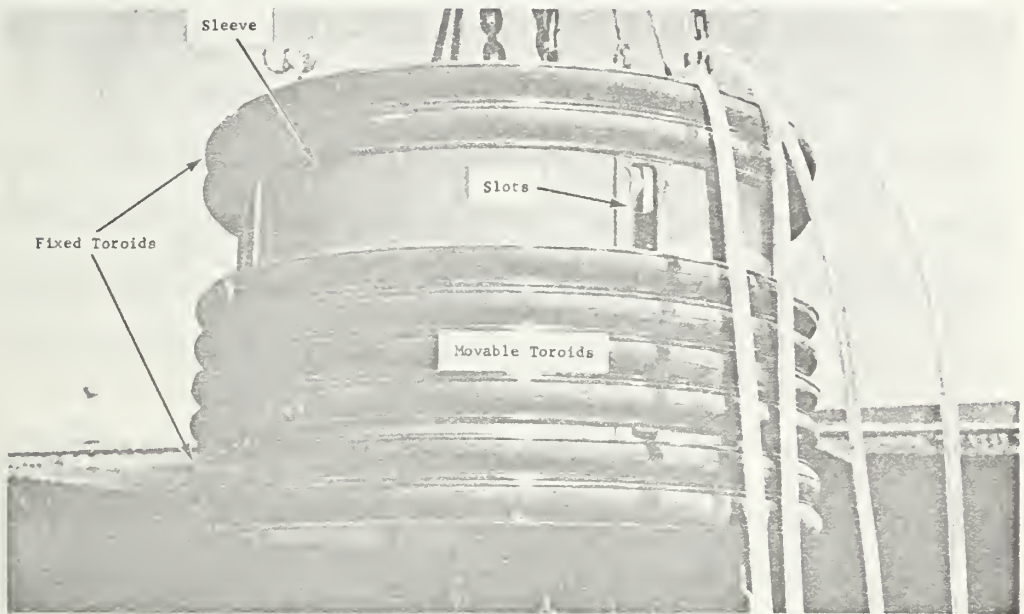
FIGURE 2.10 U.S. Navy Polytoroidal Tunneling
Thruster (After U.S. Navy, 1973)

Because of insufficient funding, this particular project concluded at the feasibility stage. Recently, interest has been renewed in applying this principle to horizontal drilling, however it is being considered for large diameter tunnel boring machines and not for a small diameter exploration hole.

If a method were developed to bypass the circumferential, flexible anchoring tubes, this type of thrust applicator would be very successful because of its high contact area and its inherent ability to limit side wall damage due to anchoring.

WORM^{TM} The WORM^{TM*} (Rubin, 1974) is an acronym for Wheel-less Orthogonal Reaction Motor, which was invented by W. L. Still from Aerospace Industrial Associates, Incorporated. This device, shown in Figure 2.11 also operates on the principle of ver- miculation or earthworm-like motion as described in the previous subsection. Within the WORM, this vermiculating motion is produced by "vector force cells" (Still, 1975), two radially and two axially located. These units are composed of a catalitic- cured elastomer to create a material whose properties

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[*]   The name WORM is the trade mark which the inventor intends to apply to this system. It is so identified to preclude its assuming a generic connotation (Still, 1975).

Drill String

Plenum for Instrumentation, Survey, and Telemetry Package

Worm Power and Controls

Radial Locking Cells

Axial Thrust Cells

Fluid Return Annulus

Positive Displacement Motor Inside Worm

Non-Magnetic Drill Collars

Diamond Bit
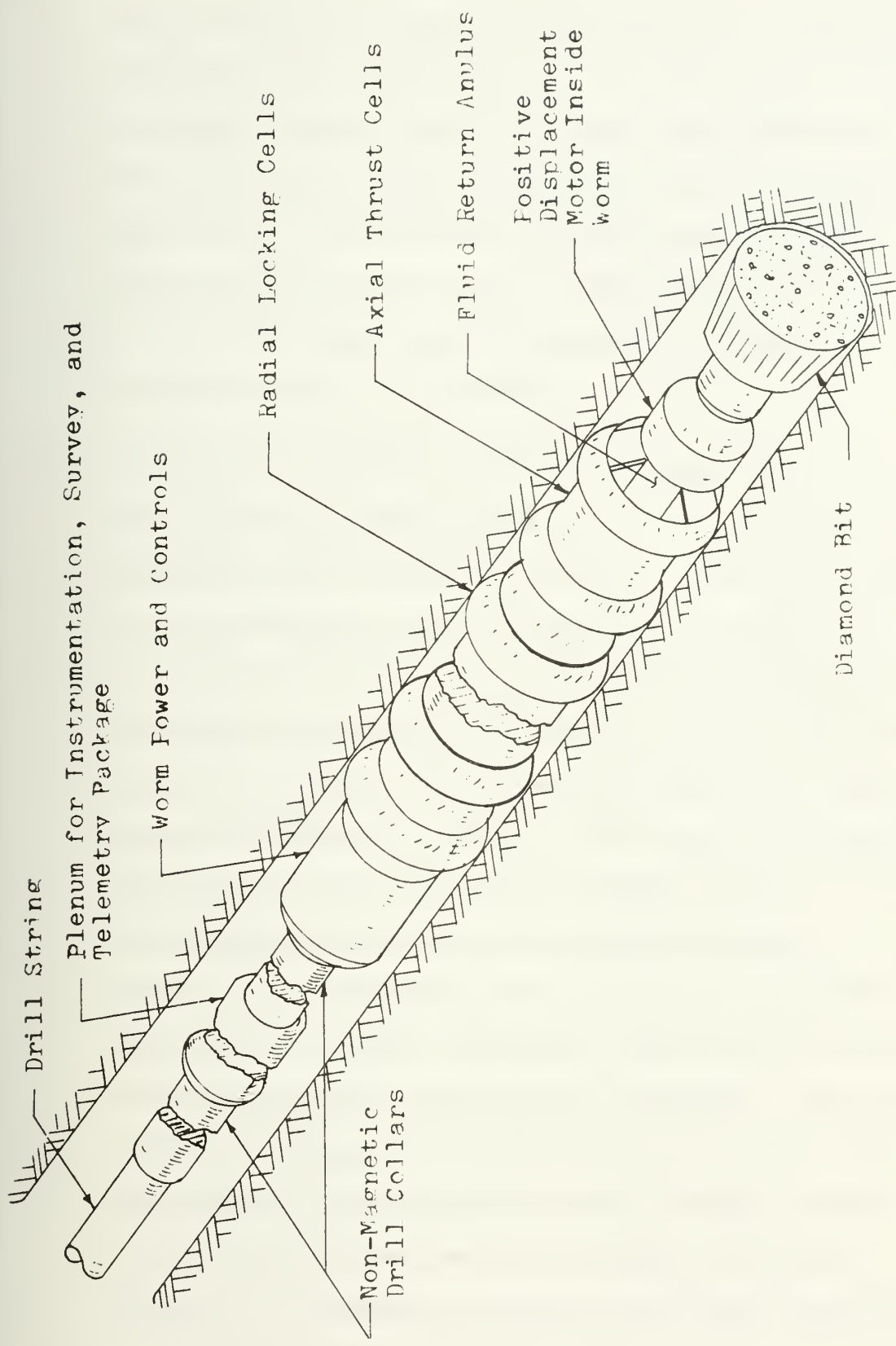
FIGURE 2.11 WORM™ (After Still, 1975)

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would sustain the abrasive environment of a bore hole.
Presently, this invention is in a model form and has
not been built or tested in a full scale version.
Mr. Still has informed the author that if the WORM
were built to full scale it would have a diameter
from 6-8 in(15-20 cm) and a length of 15-17 ft(4.6-
5.2 m). The WORM is also intended to be used with an
electric motor or a Dyna-Drill.

2.4   DIRECTIONAL CONTROL EQUIPMENT AND TECHNIQUES
        Bent Deflecting Orienting Sub A "sub" in oil well
terminology is a connecting joint. A bent sub is a
short connecting joint with the upper threads cut
concentric with the axis of the sub body while the
lower threads are cut concentric to an axis inclined
from 1° to 3° at $1/2^{\circ}$ increments from the sub axis as
shown in Figures 2.1 and 2.3. The face of the down-
hole motor is the direction in which the sub is bent.
By attaching a bent sub to a downhole motor, a
smooth arc of curvature can be drilled as compared to
the series of abrupt "dog-legs" which are associated
with the familiar whipstocking techniques. The radius
of this smooth arc is established by the selection of
the degree of bend in the bent sub. When a normal
force is applied to the drill string, a bending
moment is induced at the bent sub which results in

reactive side force being applied at the drill bit which in turn causes the bit to deviate in the direction of the motor face as shown in Figure 2.12. Therefore, the bent sub orients the drill bit in the desired direction of deviation. The drill pipe must be twisted in order to orient the face of the bit in a direction which not only takes into account the desired direction of deviation but also includes a compensating factor for the reactive torque of the motor.

<u>Bent Housing</u> This deflection technique is only available on a Dyna-Drill where the design of the interior components of the motor includes a flexible U-joint connecting rod, shown in Figure 2.13, at which point the drill motor housing is bent. The angle of bend is limited by the internal part clearances, therefore the angles are $0^{o}45'$, 1°, $1^{o}15'$, $1^{o}30'$, and $1^{o}45'$. A few of the advantages to this type of configuration are: (1) the bend is closer to the bit, thus the section between the bend and the bit is more rigid which results in less dissipation of the bending moment and side force effects on the bit, (2) the rate of angle change along the length of the drill hole increases, (3) the amount of hole damage decreases and (4) the ease of tool face orientation increases.

Bent Sub Assembly

FIGURE 2.12

Bent Housing Assembly

FIGURE 2.13

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Deflection Shoe This particular deflection device was designed and tested by the Continental Oil Company (CONOCO) as a component for their horizontal directional drilling system (Dahl, 1975). Because CONOCO has a patent application pending on this device, the level of information is restricted so as not to infringe on their proprietary rights.

The deflection shoe is extended by pressurizing an extension piston and then upon release of the pressure is returned to its original position with the help of return springs shown in Figure 2.14. The hydraulic controls are located on the surface and since the deflection shoe is directional with respect to its extension, an orientating device is also required to efficiently position the shoe.

This orientating motor is hydraulically controlled and can rotate the deflection shoe by 4° increments (Edmond, 1975). By using a predetermined reference point, the position of the deflection shoe can easily be determined.

The basic principle behind the deflection shoe is that a bit will drill in the direction in which lateral force is applied. The closer this lateral force applicator is to the bit the more effective it will be.
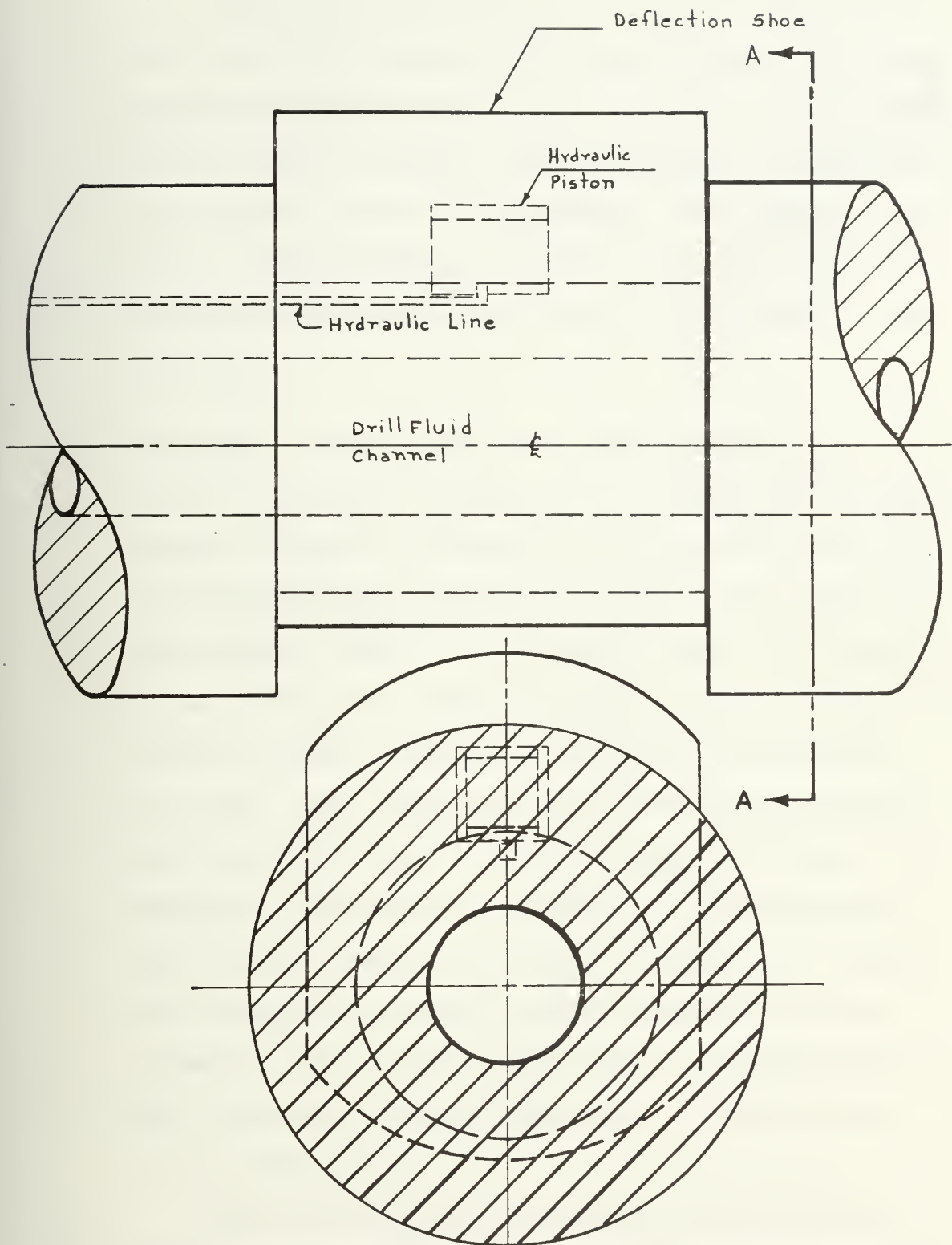
FIGURE 2.14   Schematic of CONOCO Deflection
Shoe (After CONOCO, 1975)
48

When the deflection shoe is not in use, it is flush with the adjacent drilling equipment and has a maximum travel distance of 3/8 in(0.95 cm). When the annular space dictates a greater length of extension, an extension pad can be attached. The length of the shoe is approximately 8 in(20.3 cm), while its total contact surface includes an arc of 90° over the bore hole wall.

Bit Boss The "Bit Boss" has been developed by DRILCO to provide continuous and positive directional control of the bit along with being able to be used to intentionally deviate directional holes (Garrett and Rollins, 1964). As shown in Figure 2.15, this deflection device slides over the outside of the downhole motor and has anchor shoes orientated to one side. The anchor shoes are pressurized by the drilling fluid which enters the expanding shoes through a port from the interior of the drillpipe. Due to the pressure differential between the inside and outside of the drill collar after the pump is turned on, the anchor shoes expand out against the drill hole wall, thereby applying a lateral load close to the bit.

The "Bit Boss" was developed for vertical oil well drilling, however it has the potential, after a

FIGURE 2.15 DRILCO Bit Boss (After DRILCO, 1975)

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few modifications and additions, to be applied to
horizontal directional drilling (Kellner, 1975).

Articulated Sub An articulated sub is a hydraulically
activated bent sub with an adjustable angle capa-
bility as illustrated in Figure 2.16. Bowen Tool,
Incorporated in Houston, Texas manufactures the
articulated sub in Figure 2.16 referring to it under
the trade name of Dyna-Flex[R].

     The Dyna-Flex has been developed to operate
with any air-operated or hydraulic downhole motor and
allows the motor to be selectively operated either as
a straight or directional drilling tool.
The Dyna-Flex bent sub is located directly above the
downhole motor in the same position as a fixed-angle
bent sub.

     The basic principle of operation is that the
knuckle joint shown in Figure 2.16 can be locked into
position either for straight or directional drilling
by the insertion of the proper size locking probe.
The directional angle can be from 0° to 2° at $1/2^{\circ}$
increments and is controlled by selecting a probe
whose diameter limits the angle in which the tool can
be bent. If the angle is to be changed, the probe
must be retrieved and a different diameter probe is
positioned in the tool. When operating with a
drilling mud motor, the probe is pumped down the drill

BOX SECTION
SHEAR PIN
PIN SECTION
FISHING NECK
TOP SUB
SEAL PROTECTOR RING
CAP SCREW

WEAR SLEEVE
WEAR SLEEVE SEAL
PARBAK
UPPER PISTON

CYLINDER

ROD

STEM

LOWER PISTON
STEM SEAL

CYLINDER SEAL
PISTON SEAL

COIL SPRING

CYLINDER PLUG

RELIEF VALVE
CONTROL LEVER RETAINER
CONTROL LEVER PISTON

CONTROL LEVER CAGE
CONTROL LEVER

LOWER STEM

MAIN BODY

PIVOT JOINT BODY

GREASE CAVITY

OIL RETAINER SLEEVE
LOWER SEAL CAP
CAP SEAL
PIVOT JOINT SEAL
CONNECTING BUSHING
ROTATING PIN
PIVOT JOINT SEAT

CAP SCREW
SEAL PROTECTOR RING
LOCKING PLUG
SLEEVE
PLUG SEAL
SLEEVE SEAL
PARBAK BACKUP RING
LOCKING PROBE
BOTTOM SUB SEAL
BOTTOM SUB

FIGURE 2.16   Dyna-Flex[R]
(After Bowen, 1972)

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pipe into position and retrieved with a Wire Line
Overshot. When a Mule Shoe Orienting Sub Assembly is
used for surveying, a special probe assembly must be
acquired (Bowen, 1972).

There are certain advantages in using a
Dyna-Flex Bent Sub. The directional angle can be
changed in the drill hole without pulling the entire
drilling assembly out of the hole which would be the
case if a fixed-angle bent sub were used. By changing
probe sizes, the downhole assembly can be run into
or withdrawn from a drill hole in the straight mode,
thereby reducing sidewall damage.

The only limitation on the use of Dyna-Flex is
that the smallest diameter size presently available
is 5 in(12.7 cm) O.D. However, the Bowen Tool
Company has the ability to produce a 3-1/2 in(8.8 cm)
O.D. Dyna-Flex if there is a demand for it.

Jet Bit Drilling   Another technique used to deviate
a drill hole in relatively erodable formations is jet
bit drilling. The jet bit, shown in Figure 2.17, is
a roller cone drill bit which has one of its fluid
nozzles enlarged while the remaining nozzles are
either closed or substantially reduced in diameter.
The enlarged nozzle is then oriented in the direction
of the desired deviation. Then without turning the
drill string or bit, drilling fluid is pumped through
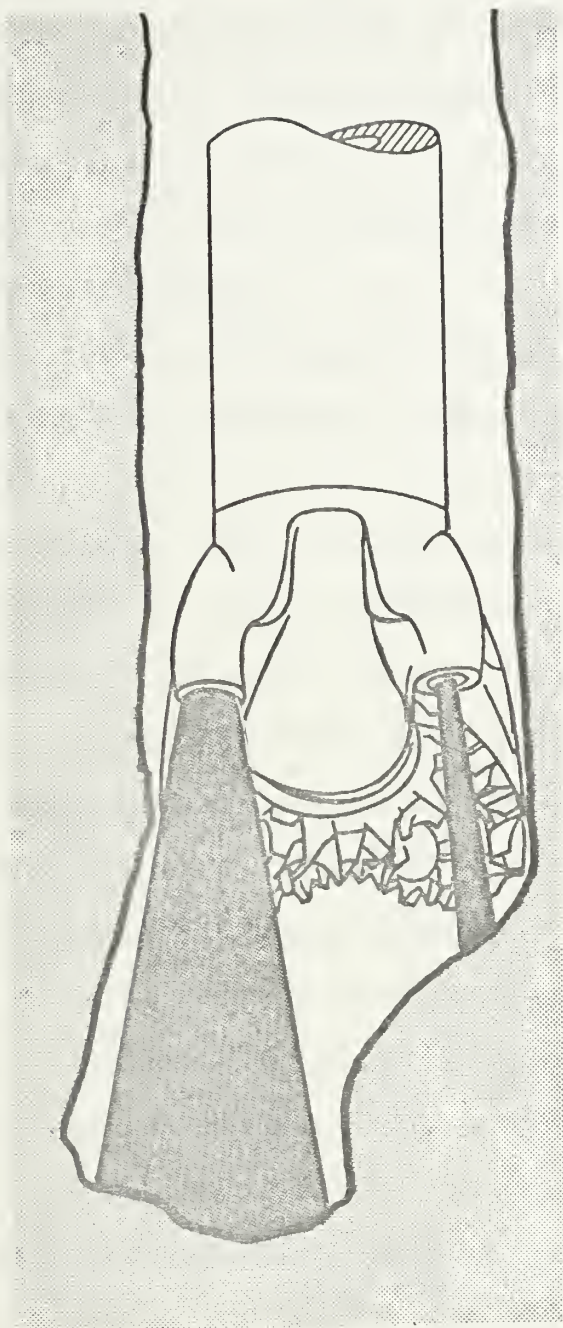
FIGURE 2.17   Jet Bit Drilling
               (After U. of Texas, 1974)

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the bit and the face is eroded unsymetrically
with the greatest erosion occurring nearest the
enlarged nozzle. By increasing the normal force on
the drill pipe, the pipe will bend in the direction
of the washed out area since this is the path of
least resistance.

Several problems are associated with jet bit
drilling in horizontal, directionally controlled
drilling in soft ground. When the subsurface soil is
clay or loose sand, jetting may result in washing out
too large of a cavity thereby decreasing the control-
lability of the drill path. Even if the enlarged
nozzle is directly up toward the ground surface, the
overextended cavity reduces the underside soil
resistance, thus resulting in the bit dropping down
under the influence of gravity.

A major reason for not being able to adapt this
type of drilling to horizontal directional drilling
involving the use of downhole motors is that as the
drilling pump is started the motor is activated
thereby turning the bit. Since the bit cannot be
maintained in one position relative to the drill hole,
the jet bit drilling technique is not compatible
with a hydraulic downhole motor.

2.5   SOFT GROUND DRILLING BITS

The various rotary drilling bits that are
presently available for use in soft formation dril-
ling are as numerous as the types of expected forma-
tions one expects to encounter. The basic external
goemetry of the three types of bits currently in use
in soft ground drilling are illustrated in
Figure 2.18.

Each one of the basic bit types has been
developed for a specific type of drilling. The
tricone is a very versatile bit with excellent
cutting ability and drills a clean, full gage hole
using a minimum torque requirement. It also has
excellent sidetracking capabilities, because of the
contact angle of the widely gapped, deep cut heel
teeth, therefore it is well suited for directional
drilling. The service life of a tricone bit is not
only a function of the wearability of the cutting
teeth but also includes the wearability of the
bearing assembly within each cone. Therefore, the
tricone bit should not be operated at high RPM,
usually not any more than 500 RPM (Hughes, 1966).
Because of the journal bearing requirements within
each cone and that some diameter downhole motors are
operated at high RPM's, tricone roller bits are not
normally manufactured less than 3-1/2 in(8.9 cm)

(After Hughes, 1975)
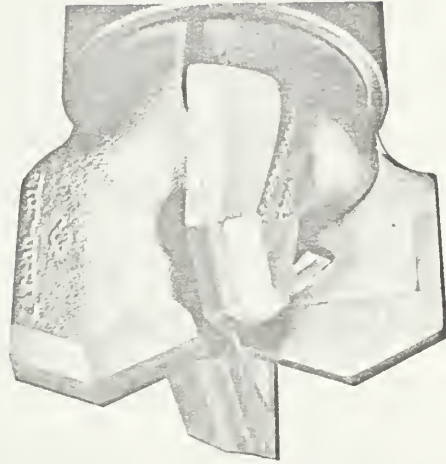
(After Hughes, 1975)
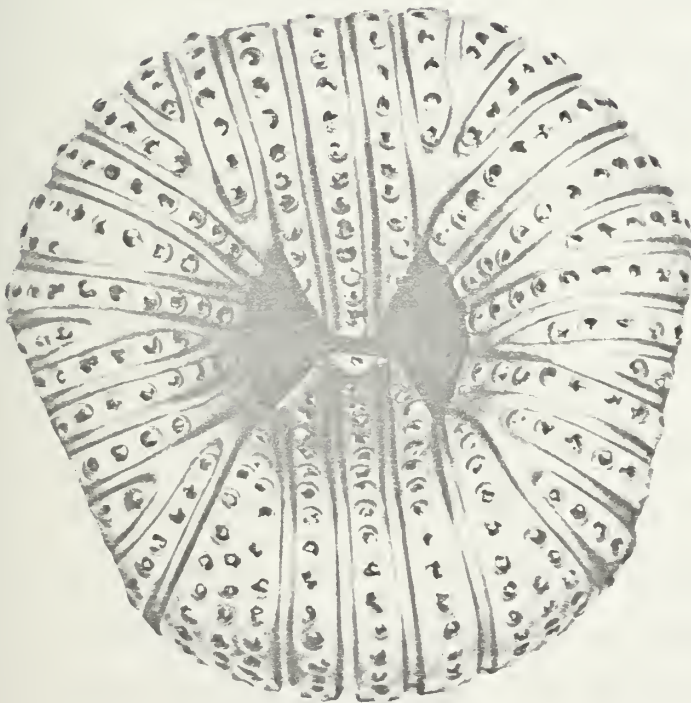
(After Varel, 1975)

FIGURE 2.18   Basic Drill Bits for Soft Ground

in diameter.

The drag bit is a good soft ground formation bit because its flat chisel shaped teeth are easily cleaned and provide the necessary tearing and gouging action required for rapid penetration. Because of the flat plate cutting surface, the drag bit requires a larger amount of torque as compared to the roller cone bit. The drag bit is the least expensive of the three types of bits and is available in sizes less than 3-1/2 in(8.9 cm) in diameter. The service life of these bits is solely a function of the cutting plate wear, therefore there is no established equipment limit on the operational RPM load for this bit.

The diamond bit is a long service life bit but also the most expensive drilling bit among the three types. The advantage of a diamond bit for soft ground tunneling is the potential one has of using one bit for the entire drill length of the drill hole. This is, however, a function of the type of formation and the normal load applied to the bit. Another positive point for the diamond bit is that it can be used at high RPM (1000+) for long periods of time while maintaining good sidetracking ability. Presently, the diamond bit is usually produced for drill holes in excess of 5 in(12.7 cm), however small diameter bits can be special ordered.

In order to select the proper drill bit, one
must consider each application on its own relative
characteristics with regard to normal load, speed of
rotation, type of soil formation, expected side
cutting loads, duration time of drilling, and the
lubricity of the drilling fluid (Allen, 1972).

There are several drill bit companies that make
standard size bits as well as specially fabricated
ones on special order. The information for this
section has been kindly provided by the Smith Tool
Company, Security Tool Company, Hughes Tool Company,
and Varel, Incorporated. The Security Tool Company
produces the small diameter tricone bits for appli-
cation in directional drilling while Varel produces
the diamond bit. Hughes Tool Company not only pro-
duces the tricone bit, but also the drag bit while
Smith Tool Company manufactures the tricone
roller bits.

CHAPTER 3

IMPORTANT CONSIDERATIONS FOR
HORIZONTAL DIRECTIONALLY CONTROLLED DRILLING
IN SOFT GROUND

3.1   INTRODUCTION

Boring a horizontal directionally controlled hole is similar to drilling a vertical hole, but yet involves a number of unique problems. In this chapter as many of these unique problems as can now be foreseen will be identified; however, some may yet be discovered due to the embryonic state of soft ground directionally controlled drilling. As accumulated experience and technical knowledge enlarges case history files, present day problem areas can successfully be eliminated.

In an attempt to address a few of those problem areas in a meaningful manner, several topics of horizontal drilling will be discussed in depth. First, the present day technique of controlling a horizontal drill path will be discussed (Section 3.2), followed by Section 3.3 on the influence of subsurface geology in controlling the direction of drilling.

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Sections 3.4 through 3.8 deal with the interaction of
the maneuverable penetration system(MPS) and the soft
ground environment. Areas of interaction include:
(1) the estimation of the required soil strength for
the operation of the thrust applicator; (2) the
bearing capacity limitations of the thruster anchor
pads and deflection shoe; and (3) the effects of soil
resistance on both of the MPS models. One of the
most critical components of any drilling operation is
the drilling fluid or drilling mud. Horizontal dril-
ling is not without exception in this area, therefore
two sections are devoted to this problem.
Finally the chapter concludes with a section on the
expected radius of curvature for the two MPS models
and the relationship of this radius of curvature to
object avoidance. Detailed calculations for all of
these areas appear in Appendix B.

3.2   TECHNIQUES IN HORIZONTAL DIRECTIONAL DRILLING

Since horizontal directional drilling has been
conducted in only a few geologic environments, the
techniques which are explained in this section might
well be out of date in a few years as new techniques
are developed and new geologies are penetrated.
However, the purpose of this section is to investigate
existing techniques and their effect on horizontal
directional drilling.

As seen in the state of the art chapter, there is a variety of equipment and methods of application for directional drilling. In order to understand how to use this equipment, one must understand the effects of gravitational force, leverage, and bending moments imposed on the maneuverable penetration system(MPS).

The first principle of directional drilling is the fulcrum principle. This principle can be understood by investigating the operation of increasing the angular rate of curvature of the drill hole in a concave upward direction as shown in Figure 3.1. The fulcrum can be a bent sub, bent housing with blading opposite the face for increased leverage, a bent Dyna-flex, or a deflection shoe. When the normal force is increased beyond that which is required for drilling, the drill pipe will bend just above the fulcrum point toward the low side of the drill hole. This leverage then induces a side force at the bit on the high side of the hole.

The flexibility of the drill pipe immediately above the fulcrum point, the degree at which the fulcrum is prebent, and the effective normal force experienced at the fulcrum, will determine the angle increase per course length of drill hole. Angle change is usually stated with respect to

Bending Force

Leverage

Fulcrum Point

Lateral Bit Force
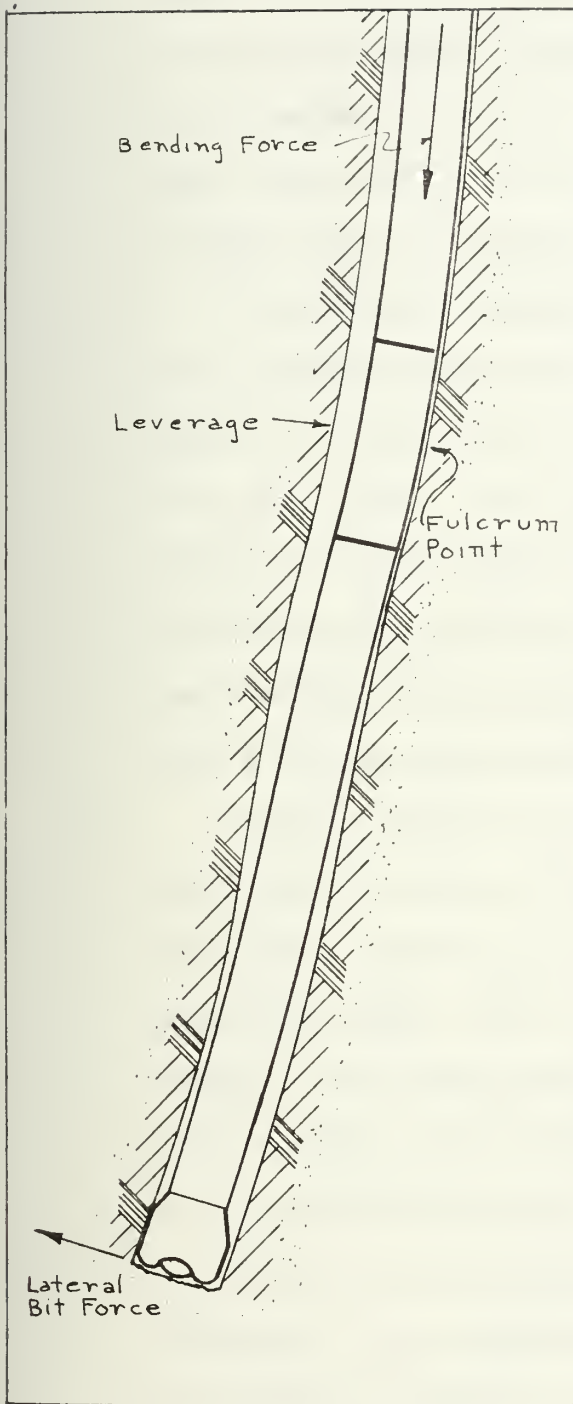
FIGURE 3.1 Fulcrum Principle

stabilizer

Pendulum

Pendulum Force
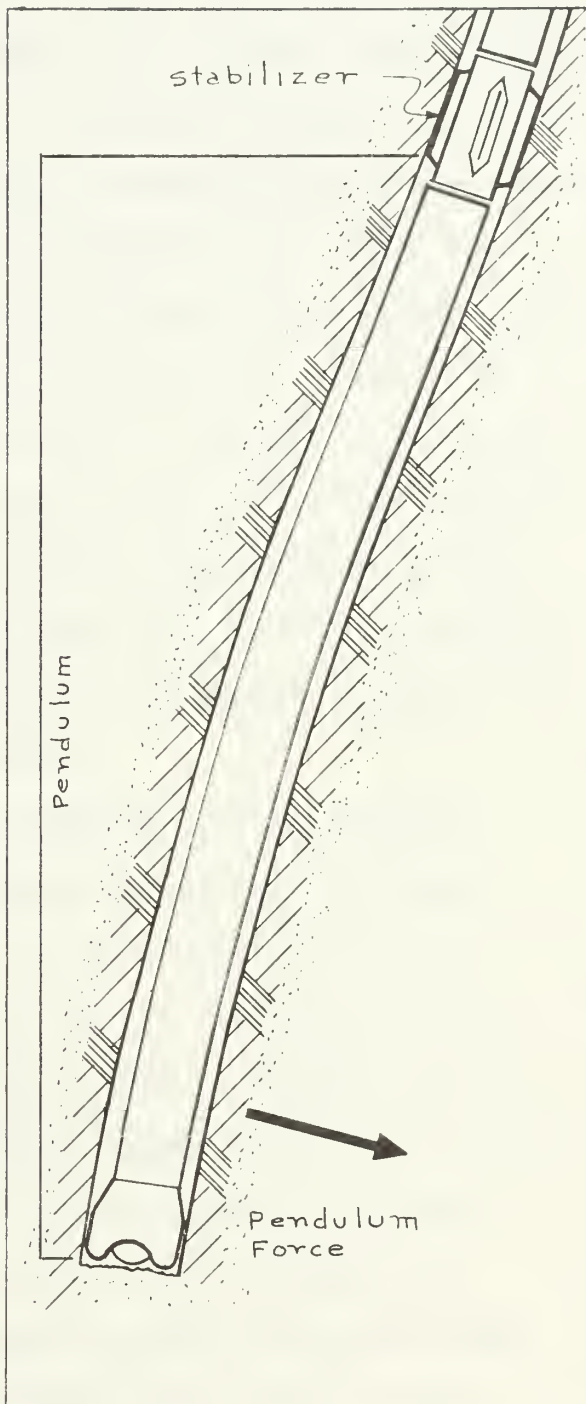
FIGURE 3.2 Pendulum Principle

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100 ft(31 m) intervals of course length. The more
flexible the drill pipe or collar, the faster will be
the rate of angle increase. In addition, the smaller
the diameter of the drill pipe with respect to a con-
stant hole size, the larger the applied leverage; hence
a faster rate of angular increase can be developed.

The second principle of directional drilling is
the pendulum principle, illustrated in Figure 3.2.
When it is necessary to drop or decrease the angle
of a drill hole, the normal forces are drastically
reduced and the gravitational forces acting on the
MPS cause the drill path inclination to drop towards
the vertical axis similar to a pendulum released
from a horizontal position.

When a bent sub is combined with a downhole
motor and the face of the motor is turned inward
toward the vertical, as shown in Figure 3.3, the
resultant effect will be that of a pendulum for two
reasons. The bent sub will apply a lateral force on
the bit while the clockwise rotation of the drill bit
will draw the bit down, thus the pendulum motion of
the drill bit is downward and inward toward the
vertical. It is important to point out again that
the amount of applied normal force and the rota-
tional speed of the bit will influence the rate of
angular change.

Bent Sub

Downhole
Motor
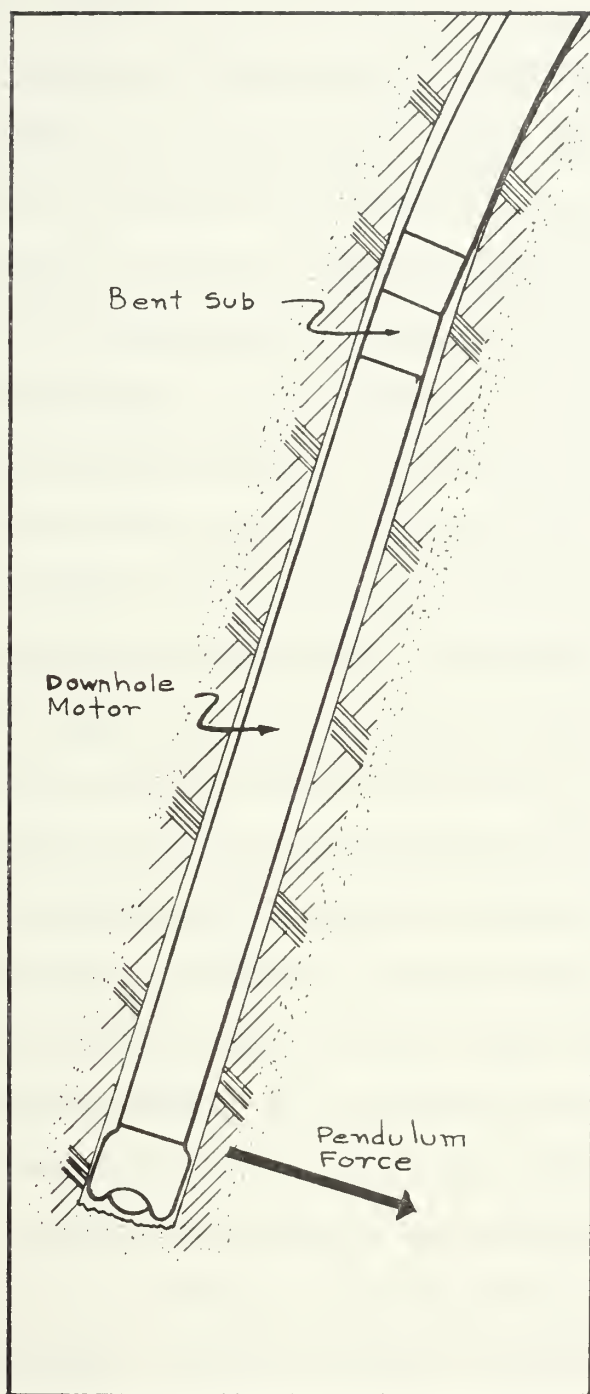
Pendulum
Force

FIGURE 3.3   Bent Sub as a Pendulum

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This pendulum motion is inherent with the in-hole thrust applicator MPS because of the clockwise rotation of the drill bit and because the relatively short cyclinder anchor pad section acts as a point of rotation for the drill bit, which can be as far as 10 ft(3.1 m) away. When the deflection shoe is not extended to compensate for the compounded effect of these two influences, the rate of angle change is significantly influenced downward.

Up to this point, increasing and decreasing the rate of angle change has been addressed. Now the technique used to maintain a straight horizontal hole for any significant distance will be treated. First, one has to understand that any hole drilled in the ground is a directional hole because it is necessary to take specific steps in order to maintain a straight hole, similar to those steps taken to intentionally deviate a drill hole (Emery, 1973). The downhole motor, in combination with the bent sub, bent housing or articulated sub, must have the motor face directed upward while maintaining the required bit speed of rotation and penetration rate necessary to compensate for the effects of gravity and the clockwise rotation of the drill bit. These same two effects are also present with the in-hole thrust applicator MPS and are compensated by orientating the

deflection shoe to the downward side of the hole and extending the shoe the necessary distance in order to maintain a horizontal course.

One of the more important considerations in directional drilling is the force acting on the bit. There are two types as shown in Figure 3.4: (1) the normal force applied by the thruster or surface support equipment, and (2) the side force resulting from the bending moment at the fulcrum. The key to controlled directional drilling is the control of the side force. The sources of this side force can be either mechanical or formation related. The mechanical sources have been discussed, therefore let us now consider the formation effects. The formation's strike and dip effect the direction and drift of a bore hole (Wilson, 1975). This formation interface in soft ground can be a clay-sand interface or vice-versa. As shown in Figure 3.5, when an up-dip formation is intersected on a plane perpendicular to the strike, the bit will have a tendency to drill up plane. If the drill path intersected the formation up-dip to the left of the strike line then it would deviate to the right while drilling upward. Then by similar thinking, when a down-dip plane is intersected, the bit will tend to drill downward and to the right or left, depending on the angle at which
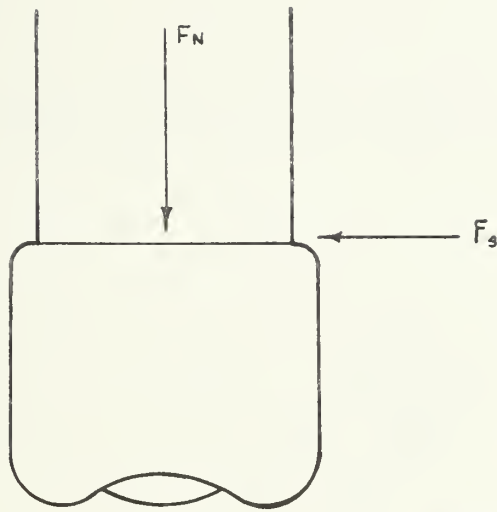
NOT TO SCALE:
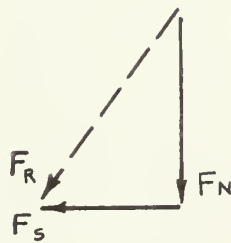
FIGURE 3.4 Forces Acting on the Drill Bit

68
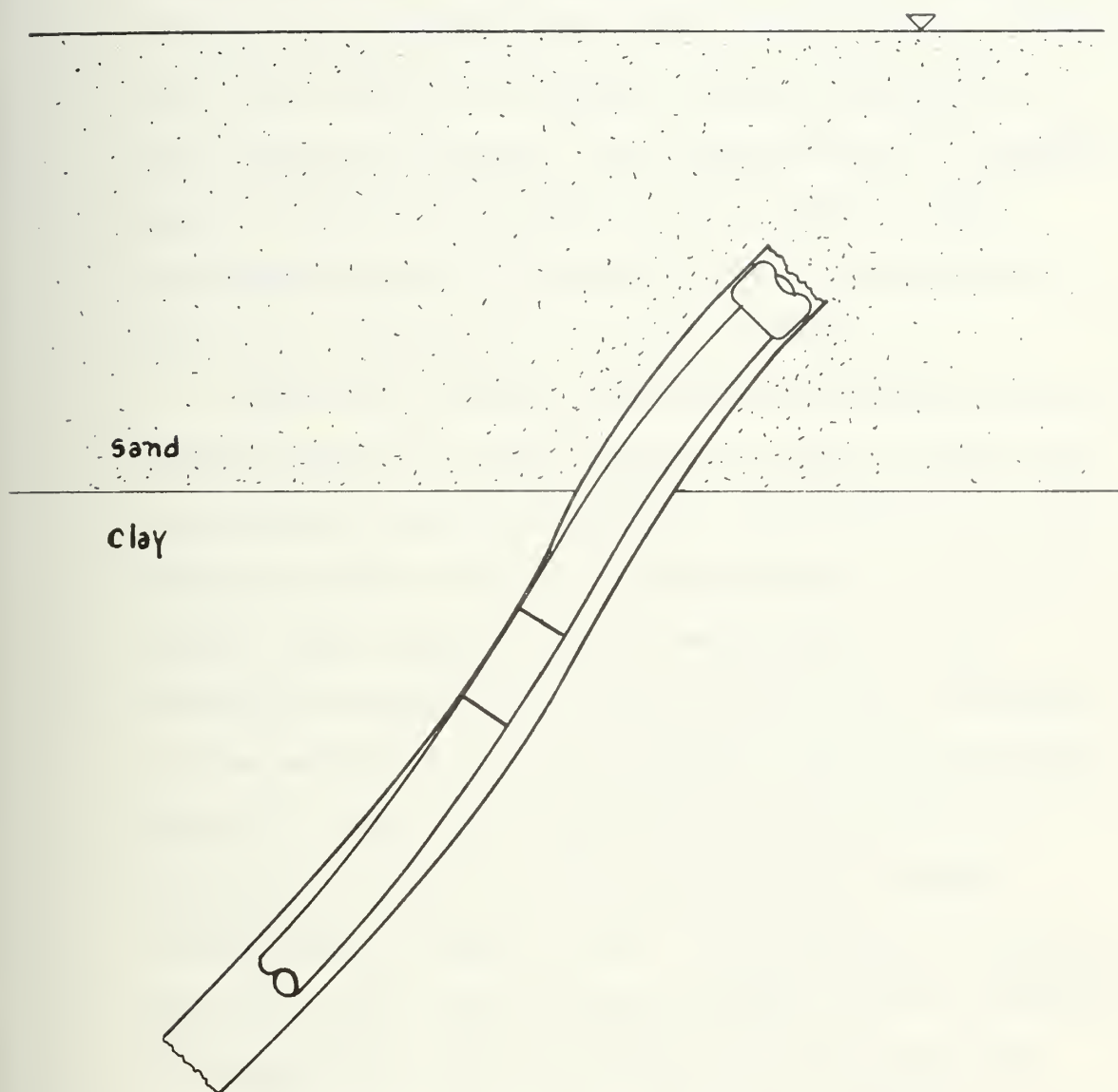
sand

clay

FIGURE 3.5 Influence of Geological Layering
on Drill Bit

the dip plane is intersected.

An alternate example in soft ground of formation deflection would be a mandrel MPS in soft clay which intersects a medium dense sand. The tendency of the drill bit will be to deflect and drill parallel to the interface surface. The primary point to remember here is that the bit will take the path of less resistance unless an external force is applied to the bit to compensate for this tendency.

The most effective directional drilling has been accomplished at a high penetration rate. Since the penetration rate is a function of the rotation speed of the bit and the rate of circulation of the drill fluid, these factors must be maintained at the optimum operating rates for the specified equipment. If the penetration rate is slower than the necessary rate for a specific formation, the bit will have a tendency to wander and control becomes minimal (University of Texas, 1974). In addition, if jetting from the drill fluid passing through the bit orifices is eroding the soil at the face of the drill bit, then an enlarged cavity will result. Control of the drill bit will again be minimal unless a high pene- tration rate is maintained to keep the drill bit as close to the face of the drill hole as possible.

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Finally, the type of drilling fluid used is very important to the success of the entire drilling operation involving a horizontal drill hole. The subject area, by itself, is so involved and has so many aspects that it could be a separate thesis. Instead, only a few topics will be discussed later in this chapter. The fluid topics will include: fluid drag forces, pressure losses within the equipment and annular space, surface pump pressure requirements to operate a downhole motor out to a distance of 5000 ft(1525 m), and the effect of the fluid pressure at the bit on the hydraulic fracture gradient of the soil.

3.3   INFLUENCE OF GEOLOGY

As with any other subsurface work, the type of geological conditions encountered will affect the choice of equipment. Therefore, in order to more effectively discuss the equipment that is available for horizontal directional drilling, the geological conditions will be defined.

Three typical urban geologies, listed in Table 3.1, have been chosen as representative of the possible subsurface conditions that exist around the major cities in the United States. The soil in Category A would be very difficult to drill in because of its soft consistency, tendency to adhere

Table 3.1 Expected Urban Geological Conditions

Soil Parameters \ Soil Category	A		B		C
	Saturated Soft Clay	Saturated Dense Sand	Saturated Overconsolidated Clay	Saturated Dense Sand	Residual
γ_t (pcf)	85-110	85-110	115-140	115-140	125-130
D_r	—	20-30	—	60-65	35-65
q_f (tsf)	0.10-0.50	—	0.50-2.0	—	—
k(cm/sec)	10^{-6}	10^{-1} to 10^{-4}	10^{-7} to 10^{-8}	10^{-7} to 10^{-8}	10^{-2} to 10^{-7}
$\bar{\phi}$	—	30°	—	$35^{\circ}-40^{\circ}$	—

to and clog the drill bit, and its very low shear
strength. On the other hand the soil in Category B
would be very drillable for the opposite reasons
previously mentioned (i.e. stiff consistency and
high undrained strength). The soil in Category C is
difficult to drill in for reasons other than those in
Category A. The residual soil can have a wide grain
size distribution which would include boulders and
clay size particles. The real problem area here,
though, is the pebble size particles ($\approx 1/2$ in(1.3 cm)
diameter). These larger sized particles will bind a
tricone roller bit and are too small for a drag bit
to crush, thus resulting in jamming. In addition, the
drilling fluid available for horizontal directional
drilling might not suspend this size particle for any
great distance. Therefore, in order to drill in
residual soil, one must have a bit that will crush
these pebbles and a drilling fluid that will keep them
in suspension until they have exited the drill hole.

The maximum operating depth for the MPS will be
500 ft(153 m) below the ground surface. Therefore, a
large percentage of the drill hole will be below the
water table. This deep operational depth will require
all of the equipment to be designed for an aquatic
environment.

Since the maximum operating horizontal distance
is 5000 ft(1525 m), certain effects on the MPS must
be considered. At 500 ft(153 m) depths, and at a
horizontal distance of 5000 ft(1525 m), the MPS will
have to overcome a sizeable amount of friction between
the soil and the trailing equipment (e.g. drill steel
or cable). The lubricity of the drilling fluid and
the neutral buoyancy of the MPS and its trailing
equipment will be a major factor in estimating this
maximum operational distance. In addition, the head
losses experienced along the drill pipe and MPS will
limit the maximum distance the MPS can effectively
drill. Both of these hydraulic topics will be dealt
with in detail later in this chapter, while all
related calculations will appear in Appendix B.

The efficiency of an operator of the MPS to
control the direction of a horizontal drill hole is
dependent upon the undrained strength of the saturated
soil. This undrained shear strength (S_u) is approxi-
mately one-half of the unconfined compressive shear
strength, as shown in Table 3.2, for several levels
of consistency (Terzaghi and Peck, 1967).
These strengths are associated with saturated, silty
clays of low permeability, usually found within the
depth limits previously mentioned.

Table 3.2   Shear Strength of Cohesive Soils
                (Terzaghi and Peck, 1967)

S_u=1/2 q_u (tsf)	Consistency	Unit Weight (pcf)
0-0.125	Very Soft	100-200
0.125-0.25	Soft	
0.25-0.50	Medium	110-130
0.50-1.0	Stiff	120-140
1.0-2.0	Very Stiff	
> 2.0	Hard	130+

The undrained shear strength will affect the
turning radius of curvature for both of the MPS's
and the bearing capacity of the anchor pads for the
DRILCO thrust applicator and CONOCO's deflection
shoe. The relationship between the undrained shear
strength and the required resistance needed to def-
lect the MPS has not been rigorously analyzed to date.
A rigorous solution of the relationship is beyond
the scope of this study. However, it is informative
to list possible boundary relationships for an MPS
drilling in soft ground. Such a list follows.

1) In soft to medium clay ($S_u \approx 0.1-0.5$ tsf) it is hypothesized that the mandrel MPS will tend to crab along its path during turning. Crabbing occurs when the heading of the drill bit differs significantly from the direction of travel of the drilling unit. The MPS will crab until enough resistance from the soil is built up to react against the drill bit and create a side force large enough to change direction.

2) In loose sand this crabbing effect will not be as severe as that experienced in soft clay. During crabbing sand grains will densify or compact until the bearing capacity increases and the soil provides the reactive force to cause turning.

3) An overconsolidated clay or dense sand will have a high enough bearing capacity to provide the necessary resistance to cause turning without the MPS experiencing any crabbing.

4) The MPS's drill path will also be affected by a change of soil conditions. For example, if the MPS is drilling in a medium ($S_u=0.5$ tsf) clay with an upward inclined path and encounters a layer of dense sand, the drill bit will be deflected toward the horizontal.

The above mentioned areas are general statements which are meant to help clarify some of the techniques and principles associated with directional drilling in soft ground. Therefore, as soil conditions and strata change, so will the manner in which the MPS will react. Herein lies the art behind horizontal directional controlled drilling.

3.4 REQUIRED SOIL STRENGTH FOR THRUST APPLICATOR MPS OPERATION

The ability of the thrust applicator to supply thrust or pulling power is a function of the shear force acting on the surface of the anchor pad.

The shear strength of the soil will be the maximum shear stress that can occur across these pads. Therefore, the undrained shear strength for clay soil will equal the amount of thrust or pulling force that can be developed by the system, divided by the total pad surface area, shown in Figure 3.6.

An estimate of S_s for a thrust or pulling force required has been made for two worst-condition situations. The first case considers the maximum thrust required while the pads are anchored in soft ground with the drill bit encountering a boulder or pinacle. This thrust is assumed to be of the order of 1000 lbf(4450 N). The second case considers the effects of dragging the thrust applicator hoses over sand without significant lubricity (normally provided by the mud cake) or hose buoyancy from any in-hole drilling fluid. In this case it is desireable to develop the full pulling force, 7000 lbf(31150 N) of the thrust applicator. These two conditions were chosen because of the differences in the required normal forces.

For the 1000 lbf(4450 N) developed thrust, the total pad surface area required to operate the thruster in the weakest clay(cohesive soil)
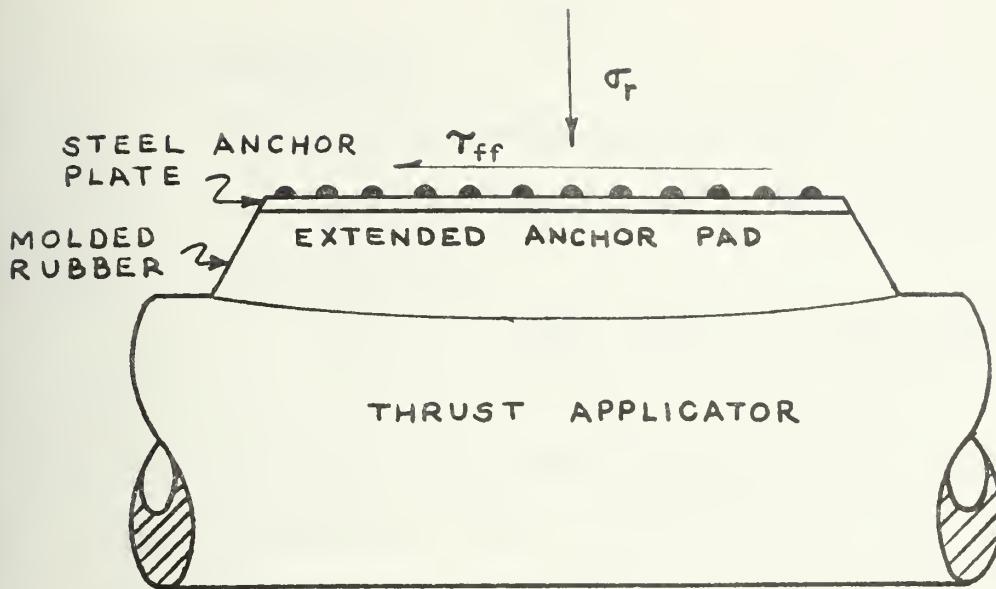
Cohesionless soil:

$$\tau_{ff} = S_s = S_d = \bar{\sigma}_r \tan \bar{\phi}$$

Cohesive soil:

$$S_s \simeq C = S_u$$

$$S_s \simeq S_u \simeq F_s / A_t$$

F_s = Shearing Force

A_t = Total Pad Area

$\bar{\sigma}_r$ = Anchoring stress applied across anchor pad surface area

FIGURE 3.6 Shear Strength Formulas

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environment is:

Thrust Requirements (F=1000 lbf)

S_u=0.25 tsf=3.47 psi(24 kN/m^2)

using S_u=F_s/A_t

A_t=F_s/S_u= $\frac{1000}{3.47}$ = 288 sq in(1858 cm^2)

The above calculation implies that 45 pads
(pad dimensions 1.06 x 6 in(2.7 x 15.2) cm)) would be
required for this soft clay soil with S_u=0.25 tsf
(24 kN/m^2). For a clay soil with S_u=2.0 tsf
(197 kN/m^2), the number of pads decreases to 35.
However, remember that this is for the worst condition.
Because of the complex interaction of the drill bit
(jetting and cutting) and the soil, there is no
reasonable estimate of what thrust requirements are
needed to drill in a total clay environment,
therefore the worst condition is analyzed.

A possible redesign was considered using a
larger surface area for each anchor pad. The new pad
size was estimated using the proportional relation-
ship between two chords at different radii over the
same degrees of arc. These calculations appear in
Appendix B.

Therefore, assuming a diameter of 8 in(20.3 cm),
the pad size might be 1.5 x 8 in(3.8 x 20.3 cm) with
a pad area equal to 12 sq in(77.4 cm^2).

An estimate of the minimum S_s required for various numbers of pads was then calculated for cohesive soils with a bit normal force requirement of F=1000 lbf(445 N) and the relationship,

$S_s = S_u = F_s/A_t.$

Table 3.3 Minimum Required Shear Strength

	Number of Anchor Pads					
	6	9	12	15	18	21
Minimum Required Shear Strength (tsf)	1.0	0.67	0.50	0.40	0.33	0.29

The same calculations were performed to estimate what minimum S_s would be required to pull the three thrust applicator fluid hoses along various hole lengths. As was previously stated, these hoses are assumed to rest on the bottom of the hole in sand (i.e. worst condition possible, short of hole collapse). Therefore, the thruster must overcome the frictional force of the hose resting on sand without buoyancy, as shown in Figure 3.7

Figure 3.7 Friction Forces Acting on Thruster Hose
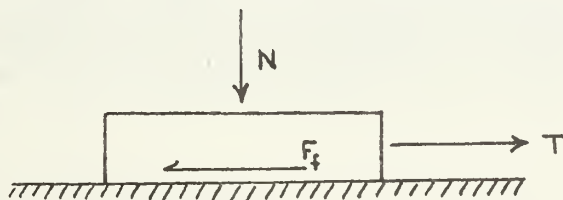
$T > F_f = \mu N$

The results of these calculations appear in Table 3.4

for a thruster with twelve cylinder pads (1.5 x 8 in).

Table 3.4   Minimum Required Shear Strength to Pull
            Thruster Cables

Tunnel Length (ft)	1000	2000	3000	4000	5000
Friction force component from hose weight (lbf)	360	720	1080	1440	1800
Minimum Required Shear Strength (tsf)	0.18	0.36	0.54	0.72	0.89

3.5   BEARING CAPACITY REQUIREMENTS FOR THE THRUSTER PADS AND DEFLECTION SHOE

The bearing capacity calculation will take into

account two different soil types (cohesionless-sand;

cohesive-clay), therefore, two different bearing

capacity formulas will be applied with the following

assumptions:

1) The DRILCO Thrust Applicator anchor pad
or the CONOCO deflection shoe contact surface is
assumed to be flat (for ease of calculations)
with a minimum dimension equal to the length of
the chord over the arc of the original shoe.

2) The bentonite filter cake that is
present in the drill hole sides, as a result of
using a mud slurry, will be displaced by the
anchor pad/deflection shoe upon contact so that
the pad/shoe bears directly on the sand.

3) The effect of the drilling fluid pres-
sure in the hole on the soil on either side of
the anchor pad (or deflection shoe) will in-
crease the bearing capacity as shown in Figure
3.8.
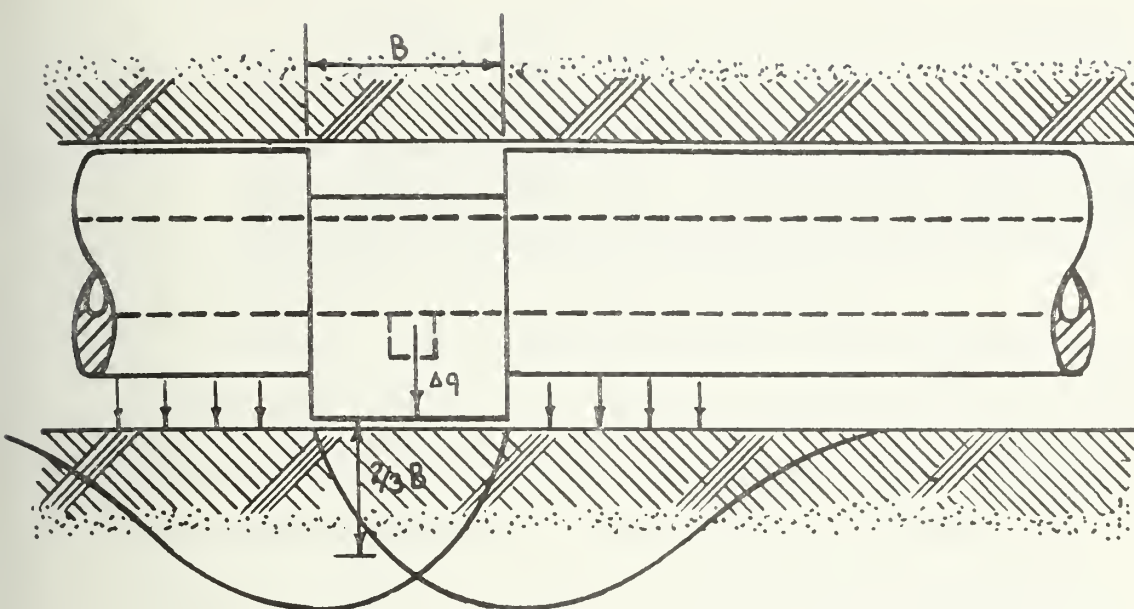
For clay: $\Delta q_{ult} = N_c S_u + P_a$

For sand: $\Delta q_{ult} = \frac{1}{2} S_\gamma \gamma B N + P_a$

Δq = Applied Stress

P_a = Annular Drill Fluid Pressure

S_γ = Shape Factor (Vesic, 1973)

N_c = Bearing Capacity Factor
(Skempton, 1973)

N_γ = Bearing Capacity Factor
(Vesic, 1973)

B = Minimum Base Demension

FIGURE 3.8 Bearing Capacity Equations and
Assumed Failure Mechanism

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4) The load on the anchor pad is uniform and normal to the drill hole wall.

5) A punching bearing capacity failure will occur when the maximum contact stress exceeds the bearing capacity. The maximum contact stress is that which is available over the anchor pad at maximum hydraulic pressure without causing the anchor pad rubber to rupture.

First, the maximum/minimum contact stress for a 5-3/4 in(14.6 cm) O.D. thrust applicator and for the deflection shoe will be calculated. This thruster is modeled because the exact maximum operating hydraulic pressure without rupturing the membrane is known. For mechanical details see Appendix D. However, a modification would have to be made to the external dimensions of the anchor pad (contact area) for soft ground application. An extension pad, with contact dimensions 1.5 x 8 in(3.8 x 20.3 cm), can be attached to the thrust applicator pad. Then the maximum, normal contact stress would be the ratio of the internal hydraulic piston area to the external pad area, times the hydraulic pressure applied over the internal area.

$$\sigma_{C_{max}} = \Delta P_H \left(\frac{A_I}{A_C} \right)$$

P_H = change in hydraulic pressure (psi) necessary to anchor

A_I = pad area in contact with the hydraulic fluid

A_C = contact area of anchor pad with drill hole wall

The results of these contact stress calculations are plotted in Figure 3.9.

Next, the deflection shoe and anchor pad bearing capacities for both MPS's operating in soft and stiff clay and loose and dense sand were calculated. The results of the bearing capacity computations are presented in Table 3.5, and details of the calculations appear in Appendix B. By comparing the maximum contact stress with the bearing capacity for each MPS, both the thrust applicator anchor pads and the deflection shoe applied less contact pressure than the bearing capacity of the soil, therefore no bearing capacity failure is anticipated.

Table 3.5 Bearing Capacities for the Anchor Pads and Deflection Shoe

Soil	Device	S_u (tsf) γ_b or (pcf)	q_{ult} (tsf) Drill Hole Distance (ft)	
			1000	5000
Clay	Thruster	S_u=0.25 =2.0	2.93 12.36	9.27 18.70
	Deflection Shoe	=0.25 =2.0	3.05 13.32	9.39 19.66
Sand	Thruster	γ_b=47.6 =72.6	1.63 1.65	7.96 7.99
	Deflection Shoe	=47.6 =72.6	1.68 1.73	8.01 8.07
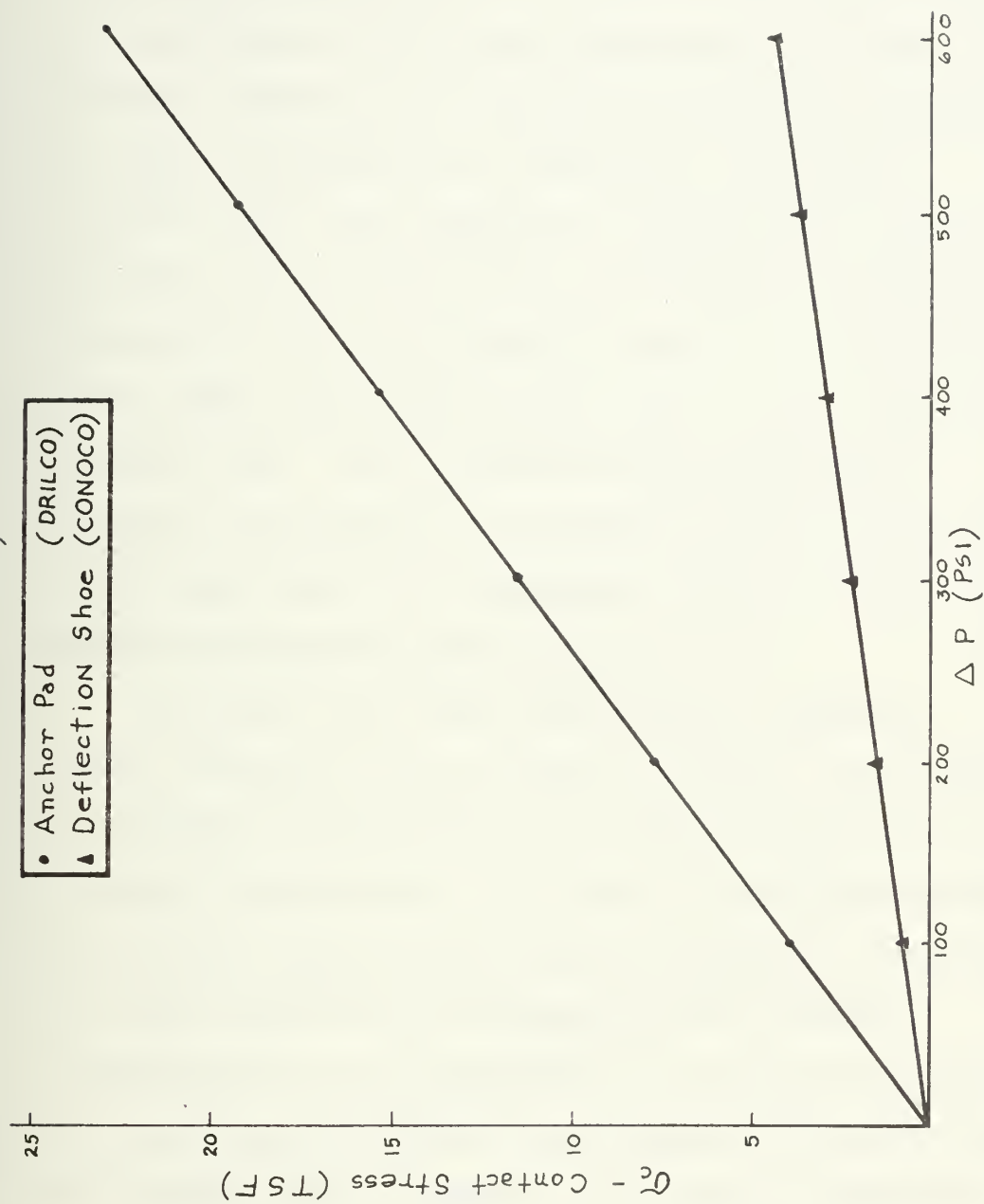
FIGURE 3.9 Contact Stress vs. Change in Hydraulic Pressure

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3.6   FRICTIONAL EFFECTS OF SOIL ON THE MANDREL MPS

Case Study-Mandrel MPS   The data for this case study
on the effects of soil skin resistance on a mandrel
MPS were taken from a directional drilling performed
by Titan Contractors in Long Beach, California.
A 1-3/4 in(4.5 cm) Dyna-Drill was used with 2-1/8 in
(5.4 cm) O.D. BQ drill pipe in 30 ft(9.2 m) sections
and a 2-3/4 in(7 cm) diameter drag bit.   The initial
entry angle and sketch of the drill rig are shown in
Figure 3.10a.   The one exploratory boring taken
showed a soil profile of a layered system of sand and
silty-sand down to an approximate depth of 85 ft(26 m)
below the original ground surface.

When the drill hole had reached a length of
about 300 ft(91.5 m), as shown in Figure 3.10a, the BQ
rod buckled on the drill rig as the carriage was ap-
plying a normal force.   In order to calculate what the
approximate applied force was at the time of buckling,
the drill pipe will be assumed to be a slender
column which is pin connected at the lower drill rig
and fixed at the carriage as illustrated in Figure 3.10b.
The dotted line in Figure 3.10b shows an exaggerated
form of the deflected BQ rig.   This deflected shape
can also be seen in the picture in Figure 3.11.

(a)

Case Study Problem
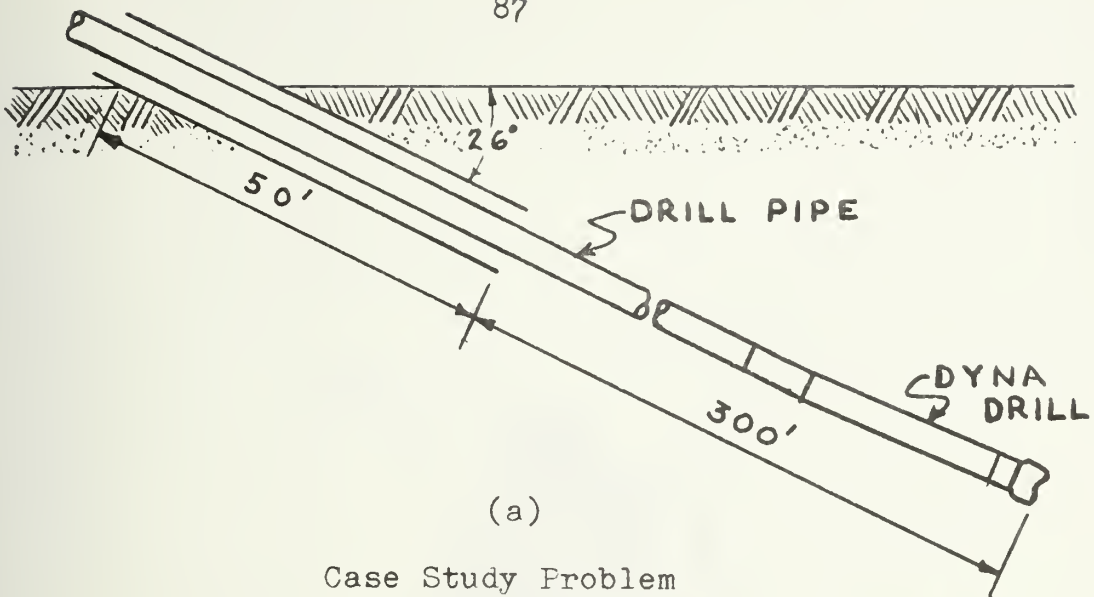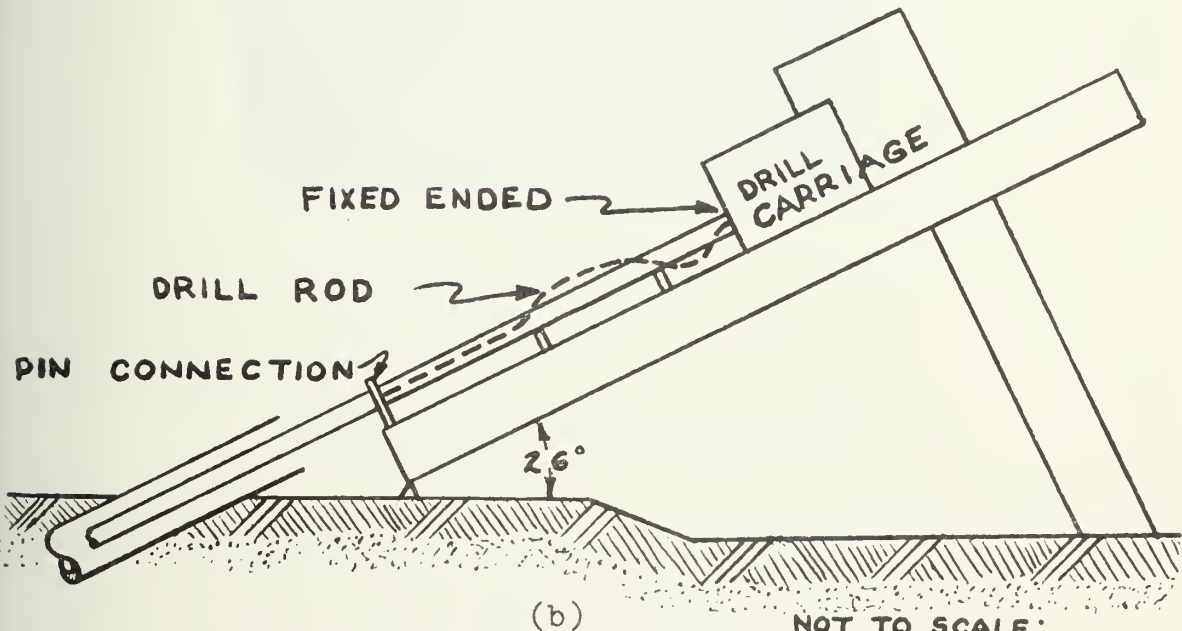
NOT TO SCALE:

(b)
Titan Contractor's Drilling Rig
FIGURE 3.12

FIGURE 3.11 Deflected BQ Rod

Applying Euler's slender column buckling criteria the critical normal force was calculated as 2.68 Kips (11926 N).

The unit skin resistance of the mandrel MPS is calculated using a relationship similar to the skin resistance along a pile. The total contact area is $A_c = \pi dL$ and the shear resistance is:

$$\tau_{fric} = P_{crit}/A_c = 0.112 \text{ psi}(0.773 \text{ kN/m}^2)$$

This is the assumed skin friction on the drill motor and drill pipe in silty sand conditions below the water table.

To calculate the mud slurry in this particular drill hole, the following relationships are applied for the 1-3/4 in(4.5 cm) Dyna-Drill with a 2-3/4 in (7 cm) drill bit on a 2-1/8 in(5.4 cm) BQ drill rod:

Annulus Velocity - $V_a = Q/A$

$$Q = 22 \text{ gal/min} = 0.049 \text{ ft}^3/\text{sec}$$

$$A = \frac{\pi(D_H^2 - D_p^2)}{4} = 0.0166 \text{ ft}^2$$

$$V_a = 2.95 \text{ ft/sec}(0.89 \text{ m/sec})$$

Shear Rate - $\dot\gamma_a = \dfrac{V_a}{D_H - D_p} = 56.64 \text{ 1/sec}$

V_a = annular drill fluid velocity
D_H = diameter of the drill hole
D_p = outside diameter of the drill pipe

From Figure 3.12, $\tau_a = 0.098 \text{ lb/ft}^2(0.0047 \text{ kN/m}^2)$.

FIGURE 3.12 Milchem Rheoplot[R]

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Then the total normal force required for an assumed neutrally buoyant MPS in mud slurry along 300 ft(91.5 m) of drill hole is,

$P_B = A_c \, \mathcal{T}_a = 18.23$ lbf (81N).

Therefore, if the annular space were large enough to provide mud slurry caking, then the maximum required normal force would be approximately 20 lbf(89 N). Instead the force on the BQ rod was very near P_{crit} which would result in buckling under the least additional resistance than already accounted for in the calculations.

To estimate what would be the ideal linear footage, one could drill under the two above sized holes (without hole collapse and ideal return flow conditions) the following calculations were made.

Applying the skin resistance per linear foot concept:

for 2-1/8 in(5.4 cm) O.D. BQ

$$A_S = 12\pi d = \frac{\pi(2.125)}{144} = 0.556 \text{ ft}^2/\text{L.F.}$$

$$\mathcal{T}_{a_1} = 0.098 \text{ lbf/ft}^2 \text{ (for 2-3/4 in hole)}$$

$$\mathcal{T}_{a_2} = 0.052 \text{ lbf/ft}^2 \text{ (for 3-1/2 in hole)}$$

$$F_{B_1} = \mathcal{T}_{a_1} A_S = 0.0549 \text{ lbf/L.F.}(0.242 \text{ N/L.F.})$$

$$F_{B_2} = 0.0289 \text{ lbf/L.F.}(0.129 \text{ N/L.F.})$$

If a factor of safety of 1.25 is applied to P_{crit}, then the maximum developable normal force(P_{op}) equals

2100 lbf(9345 N).

P_{op}/F_B = total linear operating footage

then, P_{op}/F_{B_1} = 2100/0.0545=38.5x10^3 ft(1.35x10^4 m)

P_{op}/F_{B_2}= 72.7x10^3 ft(2.2x10^4 m)

Since only the hole size differed for cases F_{B_1} and F_{B_2}, selecting the correct size drill bits for a particular drill motor and drill pipe can have a significant effect on the efficiency of the drilling operation, under ideal conditions. Of course, if the hole collapses, then the maximum penetration distance could be as low as 300 ft(91.5 m).

3.7   EFFECTS OF BORE FRICTION ON THRUST APPLICATOR

The worst frictional condition for a thrust applicator occurs when the drill hole behind the thruster collapses at a depth of 500 ft(153 m). In order to calculate the magnitude of thrust required for movement after hole-collapse, the following conditions are assumed:

1) The radial stress against the thruster hose is illustrated in Figure 3.13. The value of $\bar{\sigma}_r$=.2$\bar{\sigma}_{vo}$ is derived from measurements made on yielding tunnel liners by Hoeg (1965).

2) In order to pull the thruster hose, the sand must be failed in shear according to the Mohr-Coulomb criteria ($\mathcal{T}_{ff}$=$\bar{\sigma}_{vo}$tan$\bar{\phi}$).

3) The sand is completely saturated.

4) The soil properties are:

$$\gamma_t=120 \text{ pcf} \qquad \gamma_b=57.6 \text{ pcf}$$

$$\bar{\phi}=35^o$$

Figure content labels:

1½" O.D.

$\overline{\sigma}_r = 0.2\ \overline{\sigma}_{y_o}$

1" O.D.

½" O.D.
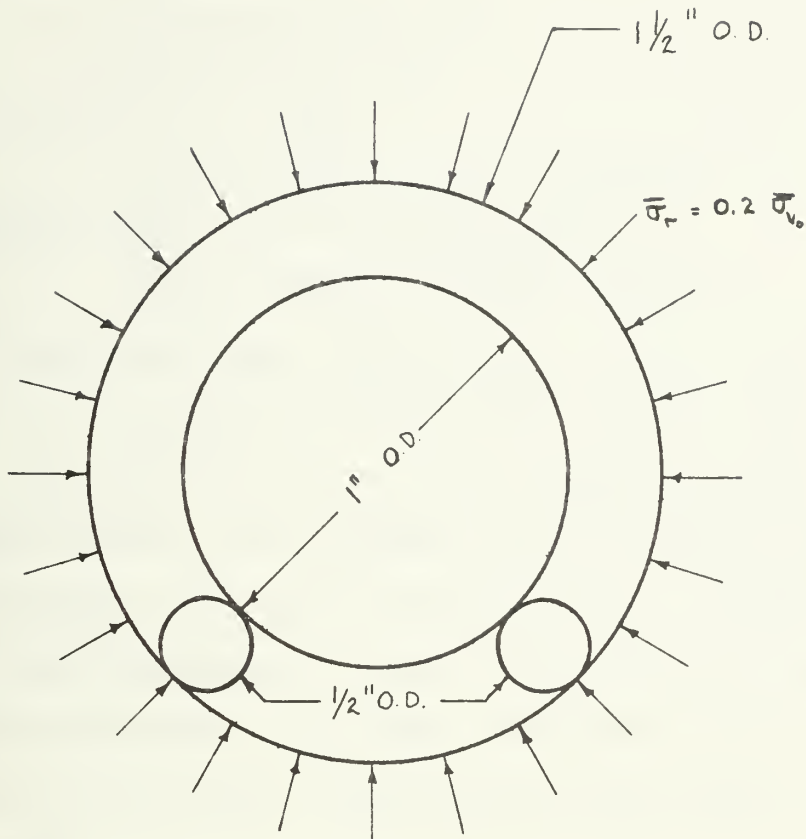
Scale: 1" = ½"

Thrust Applicator Hose - 1½in(3.8 cm) O.D.

Drilling Fluid Hose - 1 in(2.5 cm) O.D.

Hydraulic Hose   - ½ in(1.3 cm) O.D.

FIGURE 3.13 Radial Stresses Applied to the
Thruster Hose

At D=500 ft(153 m),

$$\bar{\sigma}_{vo}=57.6(500)=200 \text{ psi}$$
$$\bar{\sigma}_{r}=0.2\,\bar{\sigma}_{vo}=40 \text{ psi}$$

For a 1.5 in O.D. hose

$$A_S=12\pi d=12\pi(1.5)=56.5 \text{ in}^2/\text{L.F.}$$

Applied radial force from overburden

$$P_R=\bar{\sigma}_r\,A_S=40(56.5)=2260 \text{ lbs/L.F.}$$

For sand $\bar{\phi}=35^{\circ}$, tan $35^{\circ}=0.7$ and

$$P_{fric}=\tan\phi\,P_r=0.7(2260)=1582 \text{ lbs/L.F.} (7040 \text{ N/L.F.})$$

Therefore, in order for a thruster to pull the cable through this collapsed hole, it must be capable of pulling 1582 lbs/L.F.(7040 N/L.F.). If the maximum thrust capable of being developed by the DRILCO thrust applicator, in ideal conditions, is 7000 lbf (31150 N), then the thruster would only move 4-1/2 ft (1.4 m).

Now, if the thruster MPS is at a depth of 25 ft (7.6 m) in sand, below the water table,

$$\bar{\sigma}_{vo}=25(57.6)=1440 \text{ psi}$$
$$\bar{\sigma}_{r}=0.2(1440)=2 \text{ psi}$$
$$P_r = A_S =2(56.5)=113 \text{ lbs/L.F.}$$
$$P_{fric}=\tan\phi\,P_r=0.7(113)=79.1 \text{ lbs/L.F.} (546 \text{ N/L.F.})$$

With this hose friction, the minimum shear strength of the soil required to enable a thruster to pull a hose through a specific length of drill hole have been calculated and are presented in Table 3.6 For these

calculations, an 8 in(20.3 cm) O.D. thrust
applicator with nine 1.5 x 8 in(3.8 x 20.3 cm) anchor
pads whose total surface area equals 108 in^2(697 cm^2)
will be assumed. Therefore, $S_s=F/A_t$ where S_s is the
shear strength of the soil.

Table 3.6   Minimum Required Shear Strength to Pull
Thruster Cable through a Collapsed Hole

Length of Collapsed hole (ft)	10	20	30	40	50
Frictional Force (lbf)	739	1477	2216	2954	3693
S_s (tsf) (@ a depth of 25 feet)	0.49	0.74	1.11	1.48	1.85

To investigate the meaning of Table 3.6,
consider a thruster that entered the ground at an
angle of 30° from the horizontal and was at a depth
of 25 ft(7.6 m). The drill hole length would be
50 ft(15.3 m). In order to rescue itself, the 9
pad thruster would have to drill a vertical path
in soil with a shear strength of at least 1.85 tsf
(177 kN/m^2) or very stiff clay. The necessity for
the maximum number of thruster pads then becomes
obvious.

3.8   DRILL PATH AND EXIT ANGLE LIMITATIONS
Figure 3.14 illustrates a proposed idealized
drill path, assumed to enable some basic
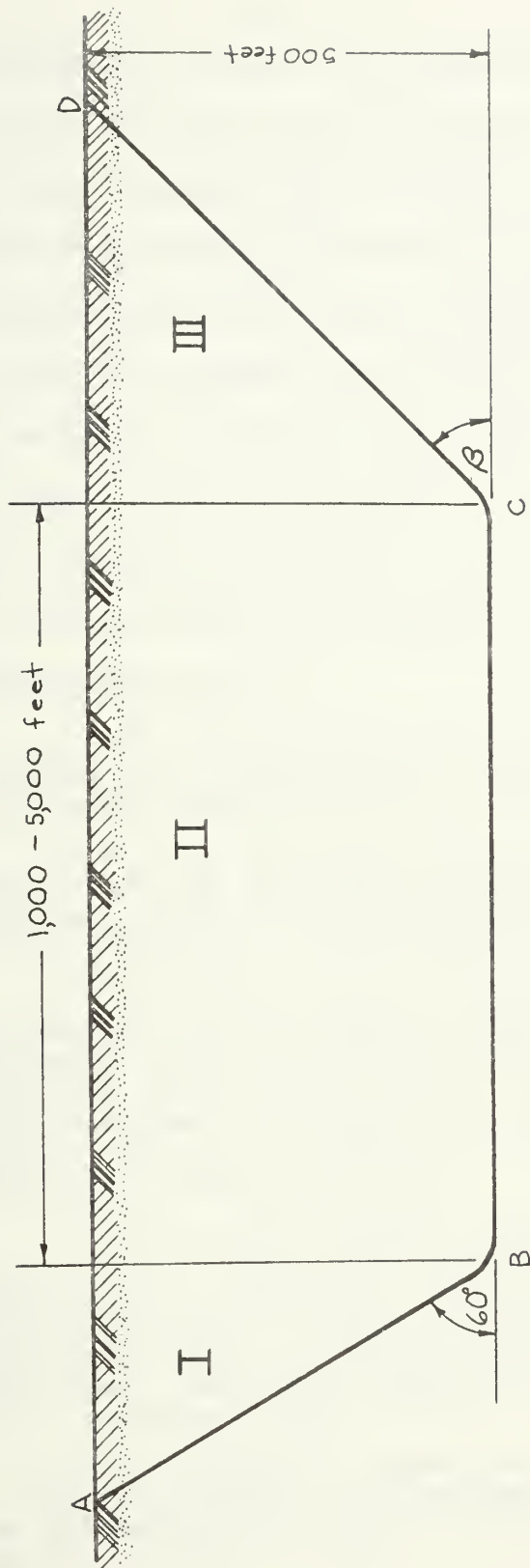
FIGURE 3.14 Proposed Drill Path

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calculations to be made for finding the maximum exit angle (β) of the drill hole. The hole is assumed to be stabilized through proper mudding techniques. In an effort to more realistically analyze this problem, pseudoplastic fluid relationships (Graf, 1971) were applied to estimate the Reynold's number, annulus velocity, and the drag forces of the drilling mud which act on the drill pipe or cable.

The following conditions and assumptions are stated to help clarify the method of approach to this multiphased topic.

1) The initial trial entry path is inclined at an angle of 60° from an assumed horizontal ground surface.

2) All of the MPS equipment is neutrally buoyant in the horizontal section of the drill path and tends to bear against the lower side of the bore hole on the inclined drill path.

3) The frictional force encountered by the MPS at the two bends in the drill path is estimated to be 10% of the total frictional component along the incline. The free body diagrams shown in Figure 3.15, illustrate the forces acting on a portion of the MPS in each section of the drill path.

4) The coefficients of friction for sands is $\mathcal{H}_s = \tan \phi$. For cohesive soils an empirical value of the frictional force per linear foot was applied for a sticky, normally consolidated soil while in overconsolidated soil the frictional force was assumed to be the same as that for dense sands.

5) The weight(W) shown in Figure 3.15 is an average weight of the system estimated at the mid-point of the drill path in Sections I and III of Figure 3.14.
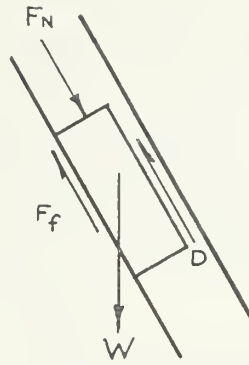
SECTION I
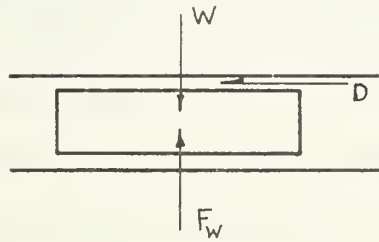
SECTION II
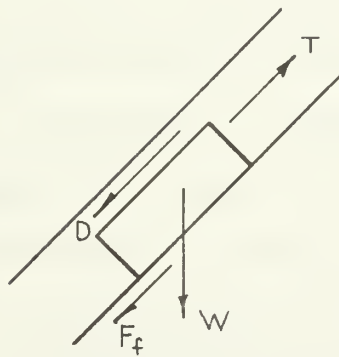
SECTION III

FIGURE 3.15 Free Body Diagrams of In-hole MPS

6) The mud slurry in the annulus is a pseudoplastic fluid and is assumed to behave according to the fluid power law, $\tau = K(du/dy)^n$, which is explained in Appendix B.

7) The soil strata is assumed constant over the depth considered.

8) The mandrel MPS used for these calculations will be a 2-3/8 in(6 cm) O.D. Dyna-Drill with a 4-1/2 in(11.4 cm) bit and 2-3/8 in (6 cm) drill pipe.

9) The thrust applicator MPS was a DRILCO unit with a 5-3/4 in(14.6 cm) O.D. with 9 cylinder anchor pads whose contact area is 1-1/2 x 8 in(3.8 x 20.3 cm). A 7 in(17.8 cm) diameter bit was used.

10) The maximum applied normal force was estimated by applying a factor of safety of 1.25 to the previously calculated critical buckling load for the drill pipe.

The calculations for estimating the maximum exit angle for both MPS's were made with respect to both a sand and clay environment.

The method of evaluation for determining the maximum exit angle is the static force balancing equations applied to the free body diagrams in Figure 3.15. The critical point of evaluation was the top of the drill path in Section III of Figure 3.14. The result of summing the forces parallel to the drill path in Section III, is the equation $F_N - F = W \sin\beta + W\mu\cos\beta$, where $F = D_T + 1.1 F_f$.

μ = coefficient of friction = $\tan\bar{\phi}$

D_T = total drag up to the top position of the incline in Section III

F_f=frictional forces acting on the
drill pipe along the incline in
Section I

W=weight of components in
Section III

Figure 3.16 was then developed from the above
relationship for various angles of β. If the ratio
of $(F_N-F)/W$ were larger than the peak value at
$\beta=60^{\circ}$, then the MPS was considered able to drill
directly vertical from a previously horizontal
path. Naturally, if this ratio were equal to a
value that corresponded to an angle between 0°-90°,
then this is the maximum β value for this MPS to be
able to exit the hole.

Calculations contained in Appendix B yielded
the following results for a mandrel MPS operating
in sand. For a drill hole with the horizontal dis-
tance in Section II of Figure 3.14 equal to 3000 ft
(915 m), the ratio $(F_N-F)/W$ was equal to 3.11 and
for a 5000 ft(1525 m) horizontal distance this
ratio was 3.05. Therefore, since both of these
values are greater than the critical $(F_N-F)/W$=1.2,
the mandrel MPS with a neutrally buoyant drill pipe
in Section II can exit vertically.

The above conclusion is based on the critical
assumptions of no buckling of the drill pipe in the
drill hole, especially in the horizontal section,
and that only the drag force of the pseudoplastic
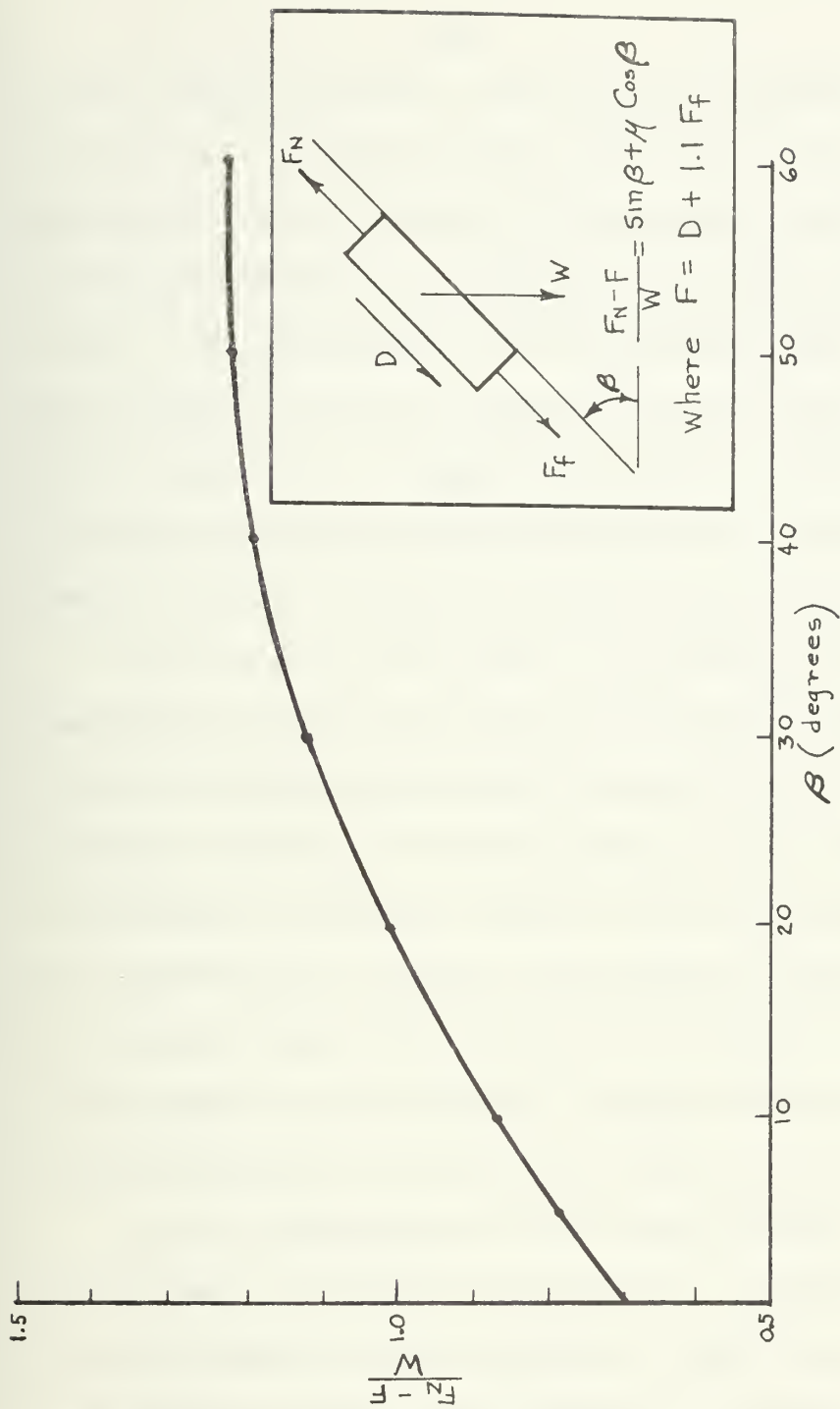
FIGURE 3.16 Maximum Exit Angle Relationships in Sand

The figure contains the following labels and equations:

$$\frac{F_N - F}{W} = \sin\beta + \mathcal{U}\cos\beta$$

Where $F = D + 1.1\, F_f$

Axis labels: β (degrees), $\frac{F_N - F}{W}$

Diagram force labels: F_N, W, D, F_f, β

fluid along the drill pipe resists movement in Section II. Another factor which had to be estimated due to the novelty of horizontal boring is the frictional effect of pushing a drill pipe around a bend. This frictional force resulting from "keying" was assumed as only a fraction of the weight of the drill pipe (i.e. $0.1F_f = 0.1\gamma W\cos 60^\circ$). This is probably an unconservative estimate of the effect of soil friction on the drill pipe at this bend.

If the drill pipe were not neutrally buoyant in Section III, what would be the resultant effect for a 3000 ft(915 m) horizontal section using $F_f = \gamma N = 0.7(3.83)(3000) = 8043$ lbf(35791 N)? Since the resistance is greater than the total available normal force at the surface, the mandrel system will not drill a hole 3000 ft(915 m) in length if the drill pipe is not neutrally buoyant and the pipe slides along the bottom side of the drill hole.

It is instructive to find the maximum horizontal penetration distance for a mandrel system without neutral buoyancy. The results of calculations found in the appendix indicate that the maximum distance is 1600 ft(488 m) along the horizontal. These calculations were made for a medium dense sand with $\bar{\phi} = 35^\circ$.

From the calculations it can be assumed that
since the thrust applicator system is a lighter
system, then it should be able to drill a further
distance in a medium sand than a mandrel system as
long as hole stability is maintained. This is, in
fact, what does result when the friction force along
the thruster hose on a horizontal plane in Section
II is added to the total friction forces. The
thrust applicator can exit vertically in Section III,
even if the horizontal distance is 5000 ft(1525 m).

These example calculations for maximum
penetration distance and maximum exit angles for
MPS's in medium dense sand indicate that the thrust
applicator would be a superior system. It is
superior for the following two reasons. First, its
lighter weight cables enable it to travel further
and secondly, the maximum available thrust is not
limited by the buckling of the drill steel. The
results of similar calculations for the two MPS's
in a clay environment follow below.

In order to calculate the maximum exit angle
for a MPS system operating in clay, a value for the
frictional forces acting on a drill pipe (or cable)
being drawn across a clay soil must be estimated.
No theoretical method in soil mechanics was found
which could be adopted to this situation and result

in a reasonable value which compares logically with
case study data. Different relationships taken from
pile load tests were investigated which included
estimating the skin resistance along the drill pipe
and multiplying by an assumed reduction factor which
resulted in an extremely high value for the friction-
al force. A similar approach was taken in an
attempt to adopt McClelland's (1974) experience
with deep penetration piles, however the adhesive
values were much higher than the case history
results. It was finally decided that since all the
pile equations included a factor for the lateral
earth pressure along the length of the pile that
this could not be correlated to a drill pipe being
drawn across the clay.

Therefore, a field value was used to
calculate the frictional force on the drill pipe
(or cable) in clay over the contact area as shown
in Figure 3.17. The data for these calculations
originates from a directional bore made by Titan
Contractors in the Wax Lake region of Louisiana.
The soil was mostly Atchafalaya clay which is a
soft, sticky clay with a low undrained shear
strength. After drilling a distance of approximate-
ly 700 ft(214 m) under a river, the 2-1/8 in(5.4 cm)
O.D. BQ drill pipe buckled at the drilling carriage
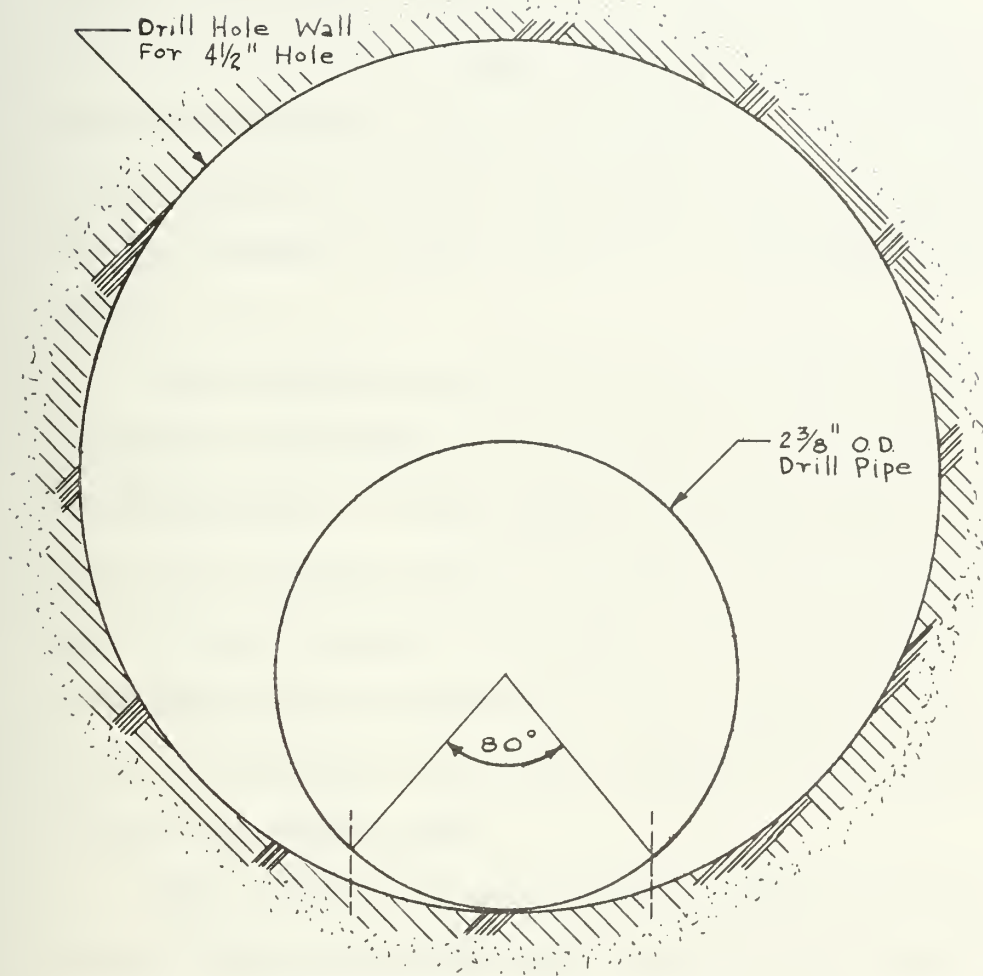
FIGURE 3.17 Drill Pipe Contact Area

as shown in Figure 3.10b. Therefore, the frcitional
force per linear foot along this BQ drill rod was
simply, P_{crit}/L.F.=2680/700=3.83 lbf/L.F.(17 N/L.F.).

This frictional value then is the upper limit
for the frictional force from a soft sticky clay
since the contact area for the smaller Titan
Contractor hole is larger per running foot than the
advanced systems considered herein. For an over-
consolidated clay, the frictional force was assumed
to be the same as that found in a saturated loose
sand.

The maximum exit angle calculations, which
appear in Appendix B, for a MPS in clay utilize the
same approach as that applied to sand, except that
now the friction force in Section III is not depen-
dent on the maximum exit angle. The criteria for
evaluation then becomes the ratio $(F_N-F/W > \sin \beta$,
where now $F=D_T+2.1 \ F_f$, for progress to be possible
at an exit angle of β.

The results for the mandrel system operating
in an overconsolidated clay yield a F_N-F/W equal to
2.67 for a 3000 ft(915 m) and 2.6 for 5000 ft
(1525 m) of drill hole.

Both of these values are greater than one
(sin 90=1), therefore the mandrel MPS should be able
to drill vertically even after drilling a 5000 ft

(1525 m) horizontal section in overconsolidated clay.
However, this is for a condition where the drill pipe
is neutrally buoyant in Section II. If friction is
considered in this section, the same results will
apply as those previously found to be true in sand
since the same friction force was assumed.

The situation is entirely different if the
mandrel MPS is operating in the Atchafalaya clay with
a high frictional force due to its "stickiness."
In fact, the mandrel system will only drill par-
tially up the incline in Section III before the
friction and drag forces would be greater than the
available normal force at the bit.

If friction were acting on the mandrel MPS in
Section II in sticky clay, then the maximum hori-
zontal distance that could be drilled is 660 ft
(201 m).

These same basic concepts were applied to the
thrust applicator MPS with only a few modifications.
Both the calculations and modifications can be
found in the appendix. The important question for
now is in what type of clay can the thrust applica-
tor operate?

The thrust applicator with the dimensions
described in the initial assumptions, can only
operate in a very stiff, overconsolidated clay

(i.e. S_u=2.0 tsf). This includes operating for a horizontal distance of 5000 ft(1525 m) in Section II.

The limiting factor for the thrust applicator system is obviously the soil to provide the necessary shearing resistance at the surface area of the anchor pads which is a function of the undrained shear strength of the soil. For example, if the undrained strength is equal to 1.0 tsf(95.7 kN/m^2) then the thrust applicator can climb an exit incline with an angle greater than 1° which is unsatisfactory.

The results of these various calculations are very interesting. If for both the mandrel and thrust applicator MPS, the drill pipe or cable could be produced to be neutrally buoyant in a horizontal drilling hole, surrounded by mud slurry, then any soil condition can be drilled and the MPS will be able to exit at angles up to 90° vertical. The only exception to this would be a thrust applicator system operating in a soft clay environment at any depth and the mandrel MPS system operating in soft clay at a depth of 500 ft(153 m).

However, if the drill pipe or cable does drag along the bottom of the horizontal drill hole the situation is reversed. The only system to operate out to 5000 ft(1525 m) in a stiff clay or dense sand is the thrust applicator system while the

maximum distance of the mandrel MPS is 1600 ft(488 m).
In a soft, sticky clay the only system to operate is
the mandrel MPS and the maximum horizontal distance
is 660 ft.

Two very important conclusions result from
these calculations. First, the effects of soil
friction on the drill pipe and cable in the horizon-
tal section of the drill hole will determine the
maximum distance that can be penetrated. Secondly,
a neutrally buoyant drill pipe or cable would be a
very effective method of reducing this friction.
However, the only cost effective solution for
neutral buoyancy is to acquire a thrust applicator
cable. This cable can be more easily produced
since a steel drill pipe would require expensive
retooling before it could be manufactured on a
production basis. In addition, neutrally buoyant
drill pipe would not be in great demand, therefore
the price would be higher than a standard stock
drill pipe.

3.9   DRILLING FLUID FLOW CHARACTERISTICS

Drilling fluid requirements for horizontal
drilling are very complex, and, in fact, an entire
thesis could be written on the subject, since there
is little knowledge of the behavior of drilling

fluids in horizontal drill holes. This novelty is
not surprising since only a small number of horizon-
tal holes have been drilled in comparison to verti-
cal holes. Nevertheless, enough information is
available to apply the fluid mechanics of a
pseudoplastic fluid in a closed conduit to estimate
various important parameters. These parameters are
the generalized Reynold's number for flow in a drill
pipe and an annulus space; drag coefficient for a
smooth pipe in an annular space and the associated
drag force; and finally the return flow pressure
losses that occur along a mandrel and a thruster
MPS. In Appendix B calculations have been made for
estimating the drag force of pseudoplastic fluid
flowing past a 2-3/8 in(6.03 cm) O.D. drill pipe
and a 1-1/2 in(3.8 cm) O.D. thruster cable.
These calculations included the generalized
Reynold's number; the coefficient of drag in an
annulus for the two previously stated MPS sizes;
and their respective drag forces. In this section
the fluid pressure loss associated with the mandrel
and thruster MPS's will be estimated for various
length drill holes. Then the pressure that is
required to force the fluid back out of the annulus
will be compared to the hydraulic fracture gradient
of the soil.

Pressure Loss for the Mandrel MPS   The mandrel MPS
for these calculations was a 2-3/8 in(6 cm) O.D.
Dyna-Drill with a 4-1/2 in(11.4 cm) bit and a
2-3/8 in(6 cm) O.D. drill pipe. The drill pipe was
assumed to be a smooth pipe for all of the Reynold's
number calculations. The Darcy-Weisbach equation
was used to calculate the pressure loss where the
"d" factor was taken as four times the cross section-
al area divided by the total wetted perimeters. The
friction factor was calculated using an empirical
relationship for laminar flow.

The pressure loss in the surface equipment will
be minimal in comparison to the in-hole pressure loss
because only a small size mud pump and short distances
of connection hose and connections are needed.
Therefore, for both the mandrel and the thruster
MPS's, the surface equipment pressure loss will be
assumed to be approximately 15 psi(104 kN/m^2).

In Table 3.7 the pressure losses for the mandrel
MPS's are summarized for various hole lengths.
Included in this table is an estimate of the pres-
sure drop across a 4-1/2 in(11.4 cm) diamond or drag
bit. In addition, there is an estimation of the
maximum pressure rating for the mud pump which is
50% above the total pressure loss.

Table 3.7   Pressure Losses in the Mandrel MPS

Equipment \ Drill Hole Length (ft)	1000	2000	3000	4000	5000
Mud Pump Hoses, Connections	15 psi	15	15	15	15
2-3/8 in Drill Pipe, Joints (Internal Flush) Drill Collar (1.995" I.D.)	26	52	78	104	130
2-3/8 in O.D. Dyna-Drill	600	600	600	600	600
4-1/2 in Diamond or Drag Bit	50	50	50	50	50
Total Equipment ΔP (psi)	691	717	743	769	795
Annulus Pressure Loss (ΔP_a - psi)	22	44	66	88	110
Total Pressure Loss (psi)	713	761	809	857	905
Estimated Maximum Pressure Rating for Mud Pump	1075	1150	1225	1300	1425

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Pressure Losses for a Thruster MPS In an effort to better compare the two MPS's the pressure losses associated with the thrust applicator MPS have also been calculated. The important dimensions and characteristics of the thruster system are:

    Thruster
        Overall length - 17 ft(5.2 cm)
        Diameter - 5.75 in(14.6 cm)
        Hoses:
            1-1.5 in(3.8 cm) O.D.
          Containing 3 hoses:
            1-1 in(2.54 cm) O.D. and
            2-1/2 in(1.3 cm) O.D.

    Hydraulic Motor - 10 H.P., 30GPM, 300 RPM
        Length - 4 ft(1.22 cm)
        Diameter - 5 in(12.7 cm)

    Modified Coring Bit
        Diameter - 7 in(17.8 cm)

The pressure losses for the thruster have been calculated in the same manner as the example calculations for the mandrel system in Appendix B and are summarized in Table 3.8.

Only one calculation requires special attention in Table 3.8. The value for the pressure drop across the hydraulic motor was calculated by:

$$\Delta P \text{ (psi)} = \frac{H.P.}{GPM}(1714) \quad \text{(Dyna-Drill, 1975)}$$

for this particular motor,

$$\Delta P \text{ (psi)} = \frac{10}{30}(1714)=571 \text{ psi}(3940 \text{ kN/m}^2)$$

Table 3.8   Pressure Losses in the Thruster MPS

Equipment \ Drill Hole Length (ft)	1000	2000	3000	4000	5000
Surface Equipment (Mud pump, hose, connection)	15 psi	15	15	15	15
1 in O.D. Drilling Fluid Hose	149	298	447	596	745
Pressure Drop Across the Nichols Hydraulic Motor	571	571	571	571	571
7 in O.D. Drill Bit	60	60	60	60	60
Total Equipment ΔP_c (psi)	795	944	1093	1242	1391
Annulus Pressure Loss $-\Delta P_a$ (psi)	42	84	126	168	210
Total Pressure Loss $-\Delta P_t$ (psi)	837	1028	1219	1410	1601
Estimated Maximum Pressure Rating For Mud Pump	1250	1550	1825	2125	2400

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Critical Annulus Pressure Analysis One of the
problems associated with estimating the annulus
pressure, using the above format, is that no consid-
eration has been given to the strength of the soil
and its ability to react to this pressure. In other
words, so far the soil wall has been treated as if it
were the inside wall of a rigid pipe.

Though the application of a common drilling mud
quantity called an equivalent circulation density
(ECD) (IMCO, 1975) and a soil mechanics property
called a hydraulic fracture gradient, the criticality
of the annulus pressure can be determined. If the
ECD is less than the hydraulic fracture gradient,
the annulus pressure should not cause loss of circu-
lation fluid into the surrounding soil of the
drill hole.

The equivalent circulating density is the
equivalent mud weight (drilling mud) needed to exert
the necessary hydraulic pressure at the bit.

$$ECD = \frac{\text{Hydrostatic head} + \text{Annular Pressure drop}}{0.052 \ (\text{length of the annulus})}$$

$$= \rho + \frac{P_a}{0.052L}$$

where ρ = mud weight

P_a = annular pressure drop (psi)

L = length of the annulus (ft)

Since the annular pressure loss increases linearly as the length of the drill hole increases, the ration of P_a/L remains constant for a horizontal section of the drill hole. Therefore, the ECD is the same value for a 3000 ft(915 m) and a 5000 ft (1525 m) drill hole length at the same depth. Added to the value of P_a for a horizontal section is the pressure head increase due to the difference in elevation. For example, at 500 ft(153 m) an increase in pressure is equal to 229 psi(1580 kN/m^2).

The annular pressure losses for both the mandrel and thruster MPS have been presented in Section 3.8 and the calculations appear in Appendix B. These values are 50% higher than the pressure loss calculated by the Darcy-Weisbach head loss equation. This was done to account for the expected increase in the drilling mud viscosity it picks up the drilling fines from the bit and carries them out of the hole. Since there is no actual data for this increase in viscosity, an assumed value of 50% of the total calculated pressure loss was used. On the basis of these latter pressure losses, ECD values were calculated for both systems at a depth of 100 ft(31 m) and 500 ft (153 m). For the mandrel MPS at 100 ft the ECD equaled 1.21 g/cm^3 while at 500 ft it was 1.46 g/cm^3.

The results for the thrust applicator MPS at 100 ft were 1.22 g/cm^3 while at 500 ft, the ECD equaled 1.49 g/cm^3.

The fracture gradients, taken from Figure 3.18 (Hedberg, 1975), indicate that the mandrel and the thrust applicator MPS system can operate at a depth of 100 ft(31 m) in saturated sand or clay without fracturing the soil thereby losing circulation fluid. However, if the MPS were to penetrate a sand where the water table was 33 ft(10 m) below the ground surface, hydraulic fracturing could occur anywhere within the first 75 ft(22.9 m) below the surface. Naturally, in completely dry sand the drilling fluid would saturate the sand and all drilling fluid would be lost in the hole.

The mandrel and thrust applicator MPS at a depth of 500 ft(153 m) both have an ECD which is very near the value of the fracture gradient for a saturated sand and above that for a sand where the water table is at 33 ft(10 m). The mandrel MPS has an ECD equal to 1.46 g/cm^3 while the thruster MPS is at 1.49 g/cm^3. Whether or not the saturated sand will hydraulically fracture is a tricky question that can only be answered by drilling in it. The author would assume that some fluid would be lost in the drill hole, however, both of these
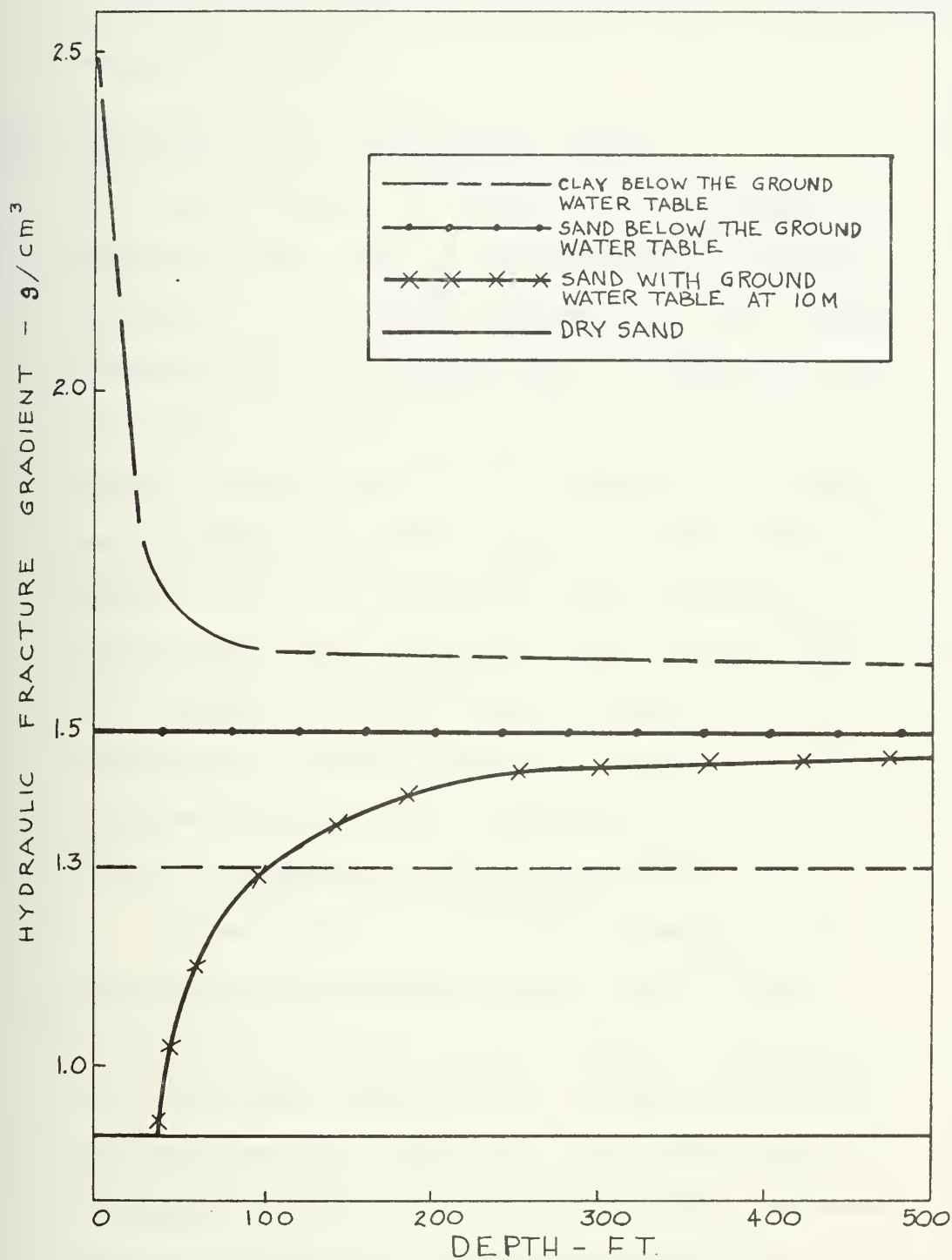
FIGURE 3.18 Hydraulic Fracture Gradient
(After Hedberg, 1975)

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systems should operate satisfactorily in a saturated clay environment.

3.10   DRILLING FLUID RECIRCULATION METHODS

As indicated in Section 3.9, the return of drilling fluid back to the surface is a function of both the soil type and equipment and the combined susceptibility to hydraulically fracture the soil. For those soils and equipment which do not hydraulically fracture, the drilling mud must be handled in a recirculation system similar to that shown in Figure 3.19. In situations where hydraulic fracturing does occur, drilling fluid may not return to the surface. The problems associated with loss of circulation are very numerous. Details on the procedures to follow when circulation is lost can be found in Applied Mud Technology (IMCO, 1974).

Figure 3.19 is a schematic drawing of the desanding recirculation system used by Titan Contractors for the Cerritos Channel crossing bore in Long Beach, California. In their system the drilling mud was pumped into the drill pipe and returned to the surface either through a washover pipe or occasionally through the drill hole annulus and collected in the earth pit as shown in Figure 3.19. This earth pit or holding tank was
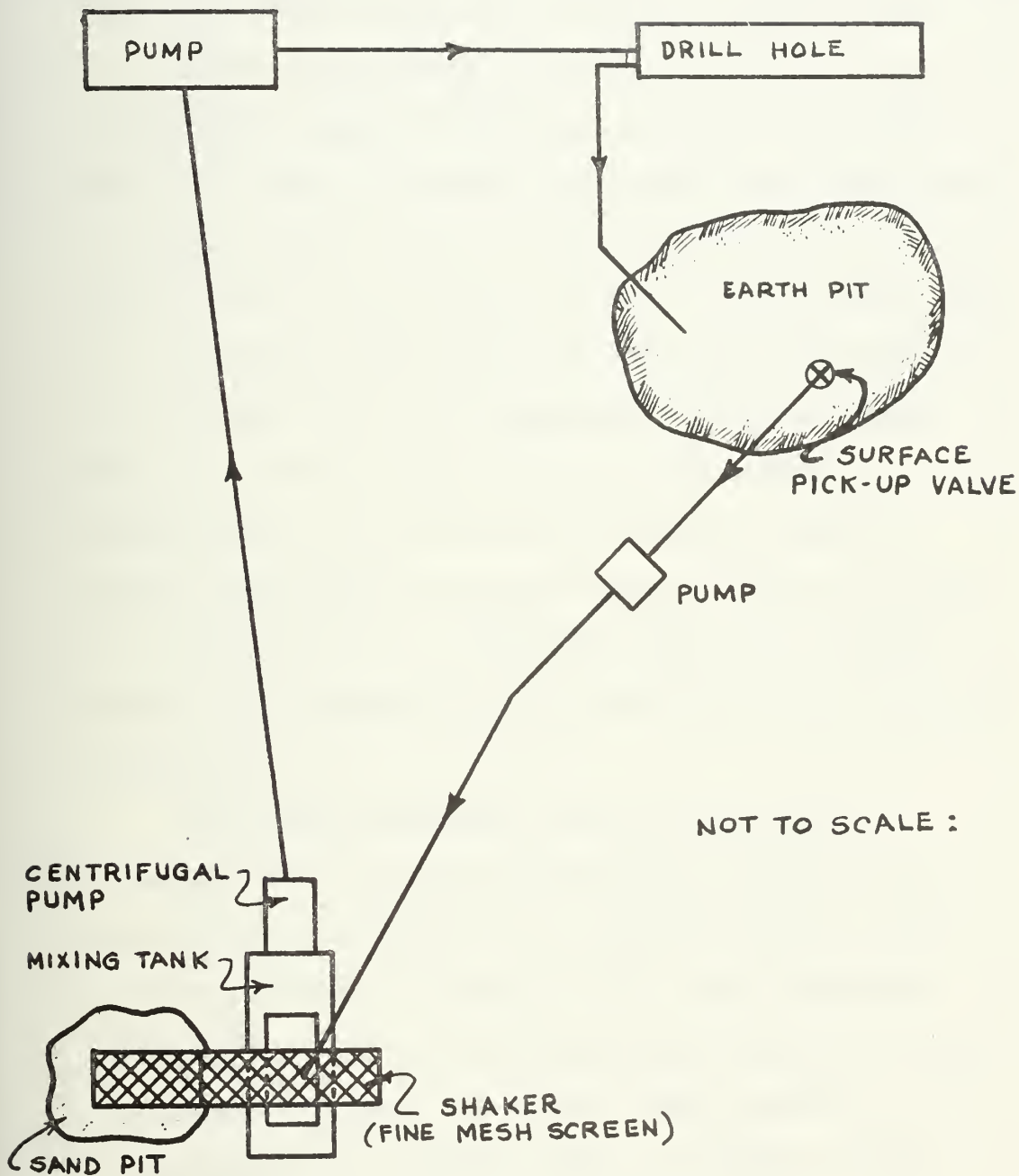
DRILLING FLUID PUMP

PUMP

DRILL HOLE

EARTH PIT

SURFACE
PICK-UP VALVE

PUMP

NOT TO SCALE :

CENTRIFUGAL
PUMP

MIXING TANK

SHAKER
(FINE MESH SCREEN)

SAND PIT

FIGURE 3.19 Desanding Recirculation System

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large enough to hold drill fluid equal to the
anticipated maximum volume of the drill hole.
The pit detains the drill fluid for a sufficient time
to allow large particles to settle to the bottom.

Sand sized particles did not settle out in a
reasonable amount of time and were separated from
the fluid with a shaker. The shaker was a fine mesh
(usually #80-#100 sieve) which was slanted over the
mixing tank in order for the fluid to be recollected
in the mixing tank while the sand was carried away
to the sand pit on the remainder of the conveyor.
The recycled drilling fluid is then blended with
additional mud, additives, and water. From the
mixing tank the fluid was returned to the mud pump
on the drill pipe to power the hydraulic drilling
motor. The operational space was not a problem at
this site.

When the operational space does become a
problem there are mud recirculation systems which
can be adopted for use on a flatbed trailer, such
as the one shown in Figure 3.20a. Mud recircula-
tion systems are a very specialized section of the
petroleum industry, therefore, each specific
application is a custom order. A typical mobile
recirculation system to be utilized with a
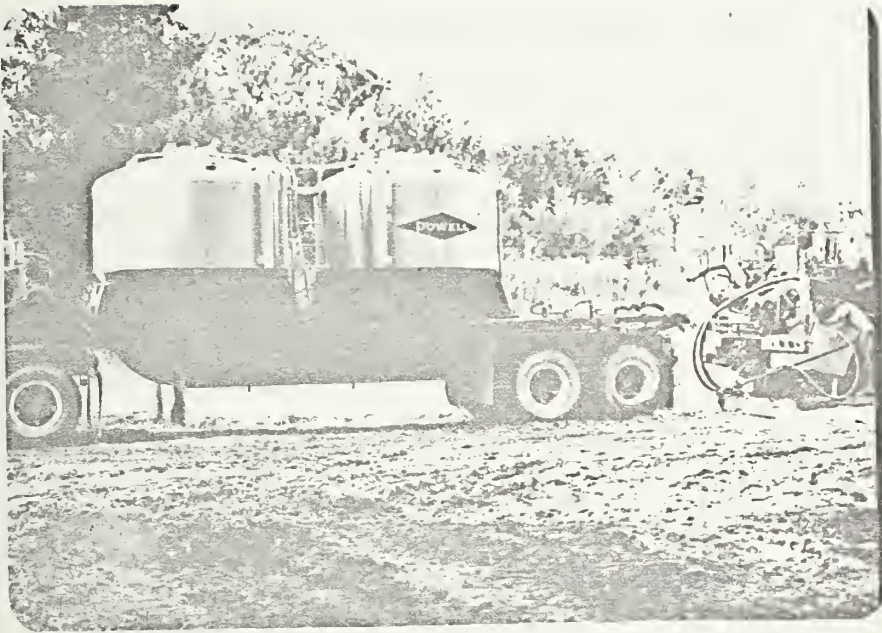
(a)
Mobile Drilling Mud Storage Tanks

(b)
Mobile Drilling Mud Pump and Mixing Truck

FIGURE 3.20

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2-3/8 in(6 cm) O.D. Dyna-Drill mandrel MPS might
include a mixer with twin centrifugal pumps
(Figure 3.20b), a carriage mounted mud pump, and a
9000 gal(34200 dm^3) settling tank. The entire
system would be a closed system which could be
adapted for use in an urban environment.

3.11   DRILL HOLE RADIUS OF CURVATURE

There are at least three reasons for measuring
the radius of curvature of the drill path. First,
an equipment limitation factor can be defined for
the mandrel and thruster MPS based on the maximum
permissible radius of curvature of the drill path.
Secondly, these equipment limitations, when combined
with the calculation of spiral path adjustments,
define minimum detection distance for obstacle
avoidance. Finally, with knowledge of the radius of
curvature the maximum depth required for horizontal
drill orientation can be calculated as a function of
the entry angle: or conversely, the minimum horizon-
tal distance required for horizontal orientation of
the drill path can also be calculated as a function
of the desired depth and entry angle.

This section will deal with these three
applications of the radius of curvature calculations.
As a first step, the radius of curvature is defined,

and its translation to build angle per 100 ft of travel (the "oil patch" approach to radius of curvature) is given. Once these basic definitions have been established, the three applications of the radius of curvature will be discussed in the above mentioned order.

Definition of Methods and Related Terminology   In Figure 3.21, the method and terminology associated with calculating the radius of curvature are illustrated. The lines 1-3 and 3-5 are tangent to the drill path at points 2 and 4, respectively, thus defining a constant radius arc. The angular displacement between points 2 and 4 is equal to angle A. By geometrical relationships, angle A, which will be designated the build angle, is also the angle of intersection between the two tangent lines.

One assumption which facilitates a simple calculation of the radius of curvature is that the arc distance from points 2 to 3a is approximately the same as the distances from points 2 to 3, for small A angles (i.e. less than $30°$), for an error less than 5%. Therefore, the resulting formula for the radius of curvature(R) is: $R = l_s/2(\cot(A/2))$.

The relationship between the radius of curvature, the horizontal displacement, depth, and
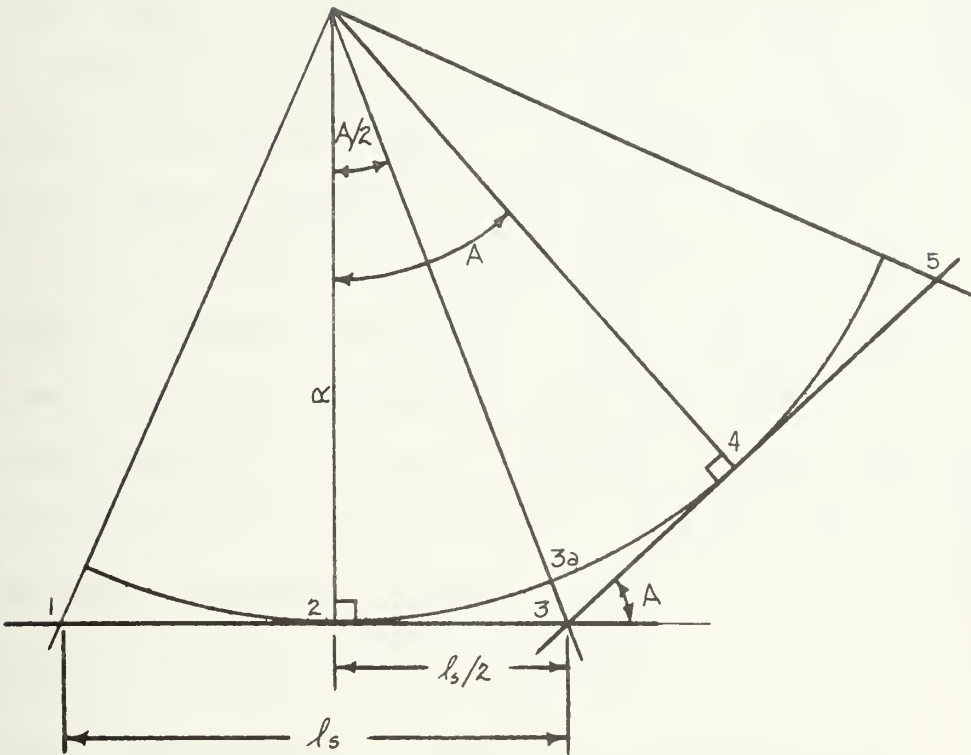
A = /l$_s$ = Rate of change of angle per l$_s$
distance (or) the build angle
per l$_s$ of distance

l$_s$ = Assumed travel distance of drill
bit between surveys

R = ½l$_s$ cot(½A) = Radius of curvature

FIGURE 3.21 Radius of Curvature Terminology

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entry angle is shown in Figure 3.22. Both the depth
and horizontal distance are a function of the entry
angle for constant radius of curvature (circular)
drill paths. The term "build angle" is basic to
both of the above geometrical definitions. Build
angle is actually an angular rate of change measured
over a specified distance of the drill path.
Traditionally, this rate of change has been expressed
in degrees of change per 100 ft of drill path. Later
in this section the effect of reducing the course
length increment will be discussed.

<u>Drill Path Radius of Curvature</u> By applying the
radius of curvature and build angle relationship,
the curve in Figure 3.23 was plotted. As can be
seen from the graph, when the rate of angular
change increases, the radius of curvature for the
drill path decreases.

The equipment limitations have been established
for the mandrel and thruster MPS and are based on
the maximum radius of curvature through which the
equipment can fit without undergoing any internal
bending moment or additional side friction from
lateral loads. In Figure 3.24 this maximum arc is
described by the three contact points: A, B, and C.
This definition for the maximum radius of curvature
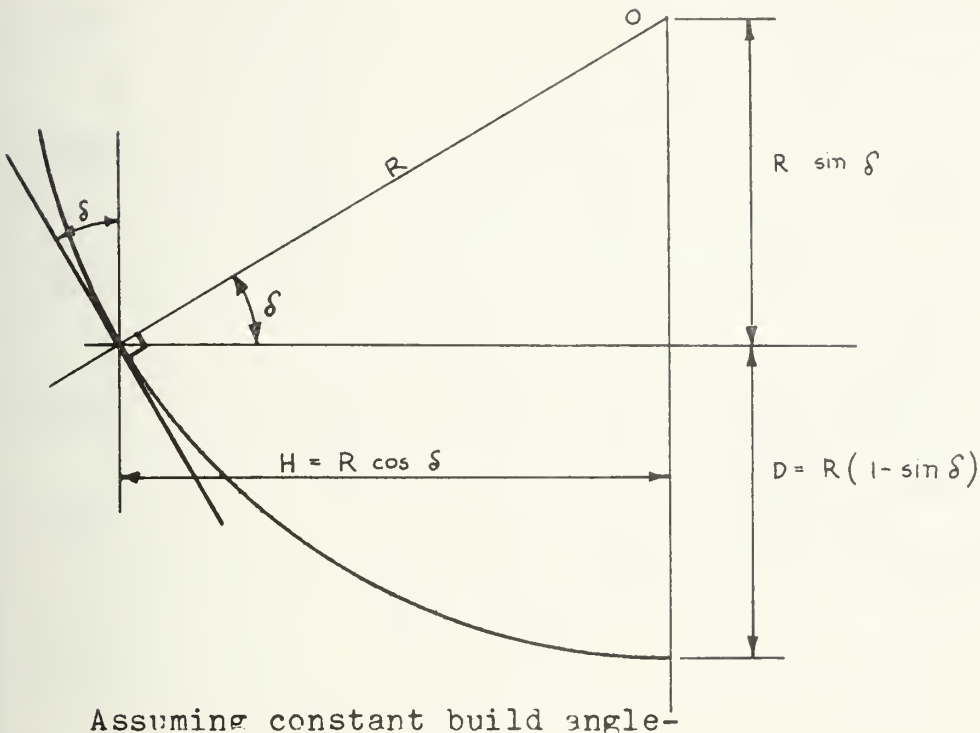
Assuming constant build angle-

δ = Angle measured between the vertical and a
tangent to the drill path at the point of
entry angle.

H = Horizontal distance from entry point to
projected vertical point at which the drill
path transverses to a horizontal plane

D = Depth when drill bit is tangent to
horizontal plane

FIGURE 3.22 Radius of Curvature and Horizontal
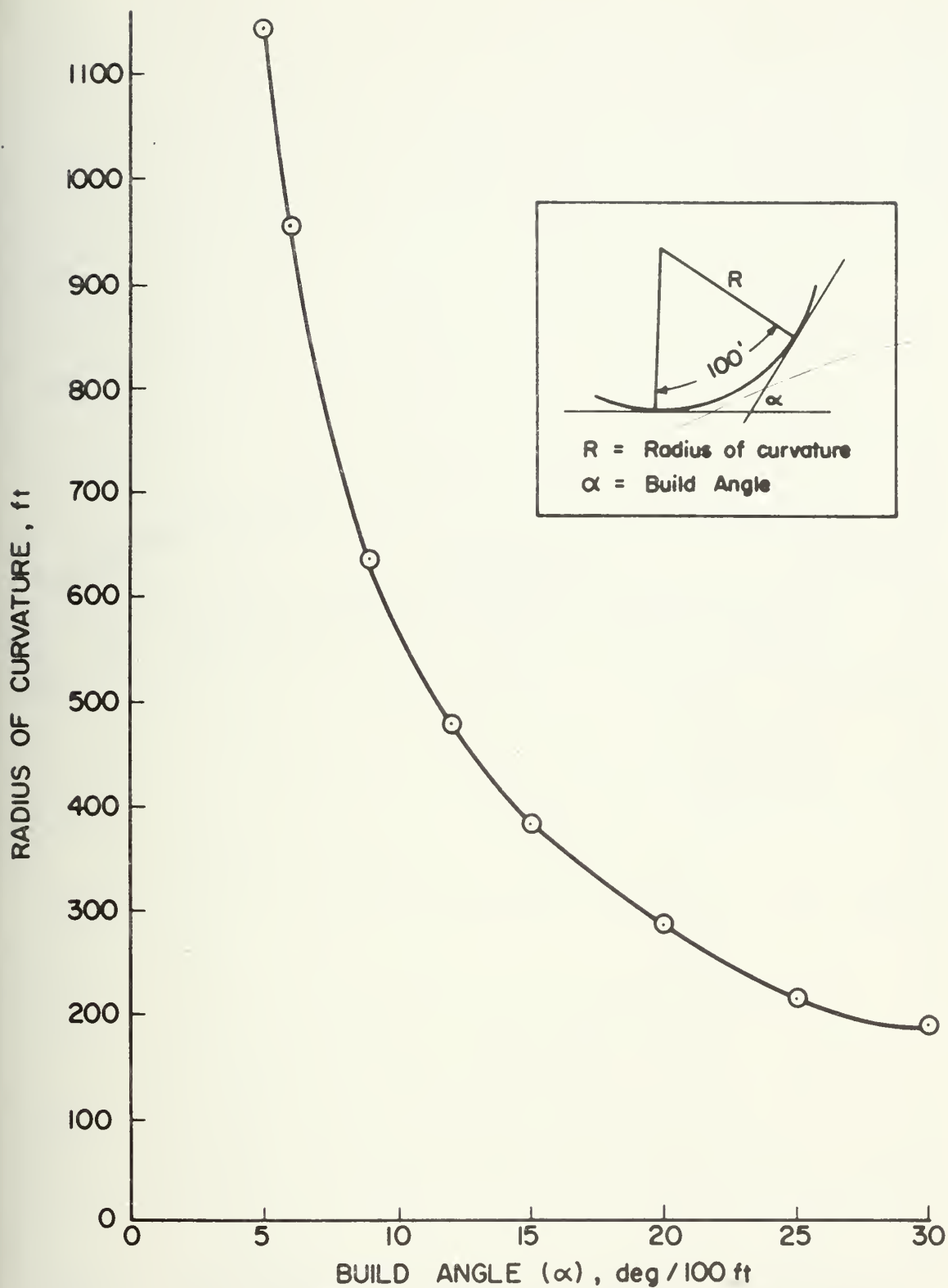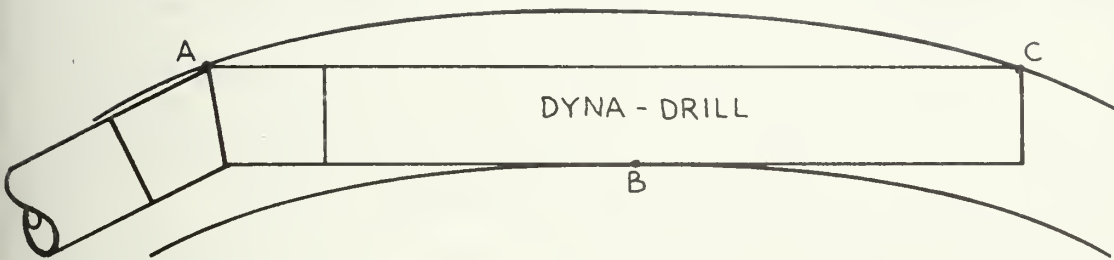Distance/Vertical Depth Relationships

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FIGURE 3.23 Radius of Curvature vs. Build Angle

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DYNA - DRILL

NOT TO SCALE:

FIGURE 3.24 Equipment Radius of Curvature Limitations

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is true for both MPS's and since both MPS's are of
similar length, the minimum value for the build angle
is $5^{o}/100$ ft($5^{o}/31$ m) which yields a radius of curva-
ture equal to 1145 ft(350 m).

The smallest radius of curvature for the two
MPS's was not theoretically calculated because of the
many unknown variations which affect this value.
Instead, field experience with the two systems has
been the limiting criterion for estimating what the
minimum radius of curvature would be if the MPS
were pushed to its limits for a short period of time.

Titan Contractors have surveyed a mandrel MPS
(1-3/4 in O.D. Dyna-Drill) drill hole and measured
an arc which correllated to a build angle of
$26^{o}/100$ ft($26^{o}/31$ m) (Emery, 1975). One point must
be emphasized, this is a maximum angular rate of
change and is not an acceptable long term operating
quantity.

For the thruster system, the maximum build
angles experienced by CONOCO have been in a range
from $13^{o}/100$ ft($13^{o}/31$ m) to $15^{o}/100$ ft($15^{o}/31$ m),
which were measured during a field test in soft coal
using the DRILCO thrust applicator (Edmond, 1975).

Combining these results with the related soil
conditions in which these build angles were measured,
a range of build angles for each MPS has been

estimated and is shown in Table 3.9.

Avoidance Distance One of the major objectives of
developing a highly maneuverable penetration system
is the ability to avoid subsurface objects.
The following presentation does not imply that these
objects are "seeable" at the calculated distances.
For more information on subsurface object recogni-
tion, the reader is directed to Hedberg (1975).

    To evaluate the ability of the drilling
equipment to avoid an object, a model of the drill
path had to be selected. A single spiral and reverse
spiral, shown in Figures 3.25 and 3.26 respectively,
were chosen over a circular path.

    The spirals were selected in place of circular
paths because of their ability to represent crabbing,
a phenomenon associated with drilling in soft
ground. Crabbing occurs when a directional change
input is made to the MPS and the MPS does not
immediately respond in changing direction along a
circular drill path. But instead, it progressively
deviates from its original drill path by decreasing
the radius of curvature as it progresses. The rate
of the progressive change of direction is believed
to be a function of compaction (in loose sands)
which increases the sand's bearing capacity and

Table 3.9 Radius of Curvature for the MPS

|	Radius of Curvature in Stiff Clay, Dense Sand (System limited) (ft)	Radius of Curvature in Soft Clay, Loose Sand (Formation limited) (ft)	Minimum Horizontal Distance (Vertical Entry) (ft)		Comments
			Stiff	Soft	
Mandrel	1145(5°/100') to 216(26°/100') Opt: 475(12°/100')	1145(5°/100') to 570(20°/100') Opt: 635(90°/100')	475	647	1) The system limit is based on the wear factor during bending of the rubber stator in the Dyna-Drill.
Thrust Appl.	1145(5°/100') to 330(15°/100') Opt: 715(8°/100')	1145(5°/100') to 380(15°/100') Opt: 715(8°/100')	715		1) The system limit is based on the minimum allowable deflection from bending which the thruster cylinder spline can withstand. 2) The soft ground limits are based on the ability of the thruster to develop thrust in this environment.

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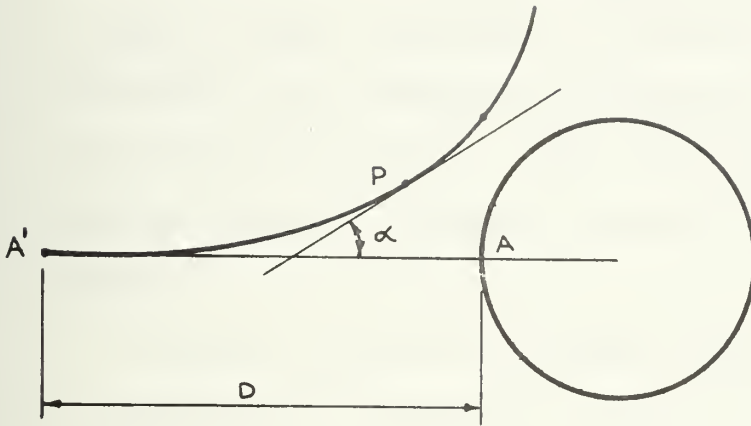
FIGURE 3.25 Single Spiral Drill Path
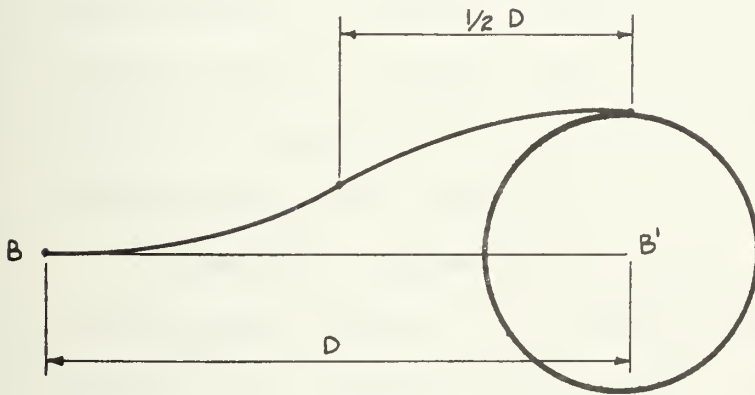
FIGURE 3.26 Reverse Spiral Drill Path

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hence its ability to resist the applied skewed load.
Since no drill hole in soft ground has been surveyed
in small enough increments to establish the exact
projectory, the existance of crabbing is hypothetical
but definitely possible. The exact soil behavior
causing direction change is beyond the scope of this
thesis.

Both the single and reverse spiral were selected
to represent two different avoidance situations. The
single spiral represents the case where object
avoidance is the only course desired without any
consideration for returning to the original direction
of drilling. The reverse spiral does take into
consideration returning to the original direction
of the drill path.

The avoidance distance "D" is defined for the
single spiral in Figure 3.25 as A-A', while for the
reverse spiral in Figure 3.26, it is B-B'. The
object's diameter is the limiting criterion for
defining these two distances.

A computer program was written to calculate
the avoidance distance for several sized objects
relative to a specific build angle. The build angle
for these calculations is defined as the angle
between a tangent to the spiral at a particular
point on the spiral and a tangent to the original

drill path, as shown in Figure 3.25. The distance
from point A' to point P in this figure has been
chosen as 100 ft(31 m).

The results of this computer program are plotted
in Figure 3.27. To find the minimum avoidance dis-
tance for a particular type of equipment, first go
into the right hand graph in Figure 3.27 with a
predetermined build angle and diameter of object to
be avoided, and find the radius of curvature for
either a single or reverse spiral drill path.
Then move across to the left hand graph with the
same radius of curvature and build angle and find
the distance required to avoid this particular size
object.

Horizontal Surface Distance Two factors affect the
horizontal distance and vertical depth at which an
MPS will reach a horizontal plane: the entry angle
and radius of curvature of the drill path. In
Figure 3.28, a vertical entry angle has been chosen
to display the variation in depth and horizontal
distance as the build angle is changed. This graph
shows the optimal continuous operating range for
both the mandrel and thruster MPS. In Figure 3.29,
the three optimal drilling paths for the two
currently operating systems are shown. These drill
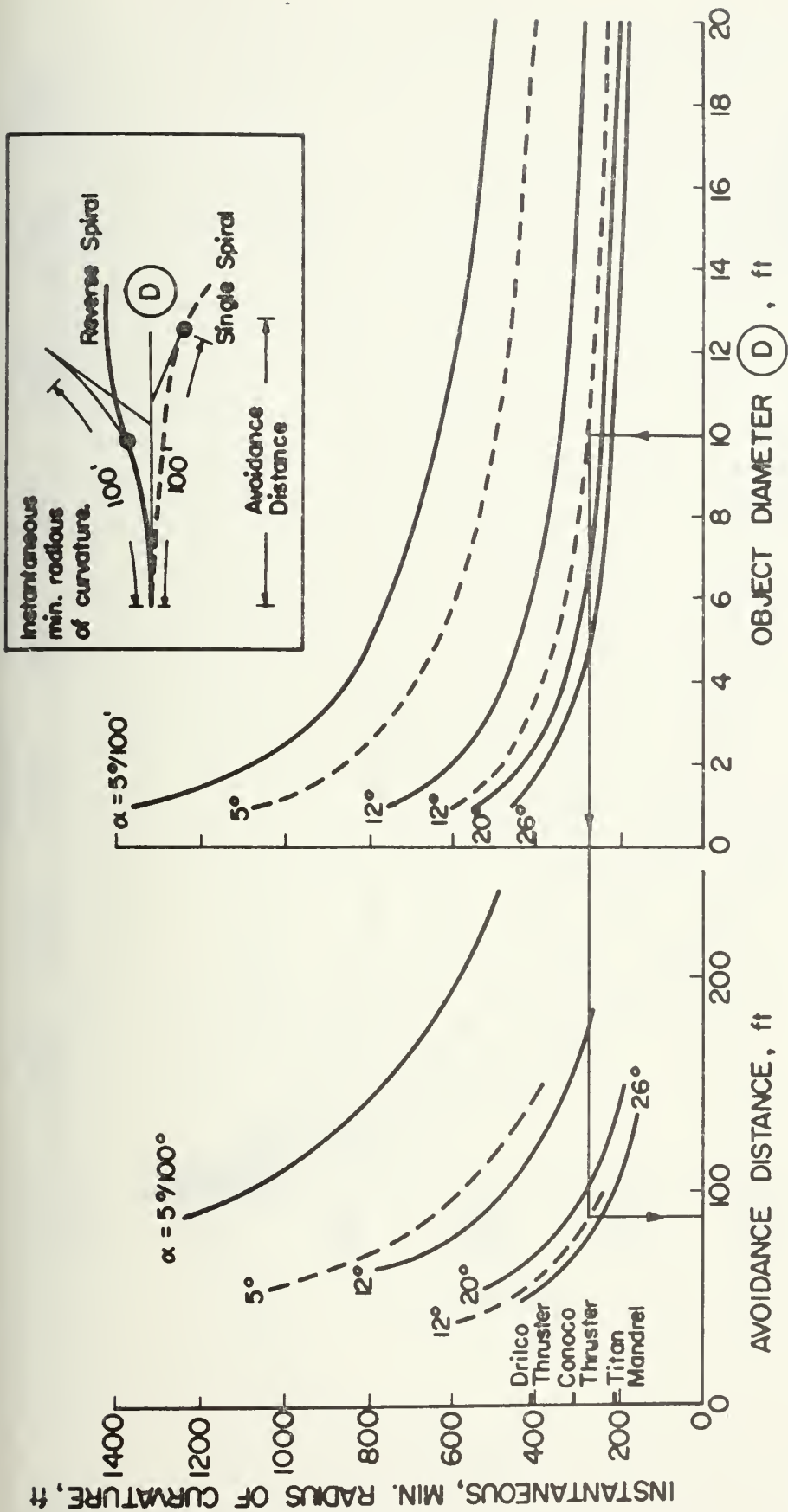
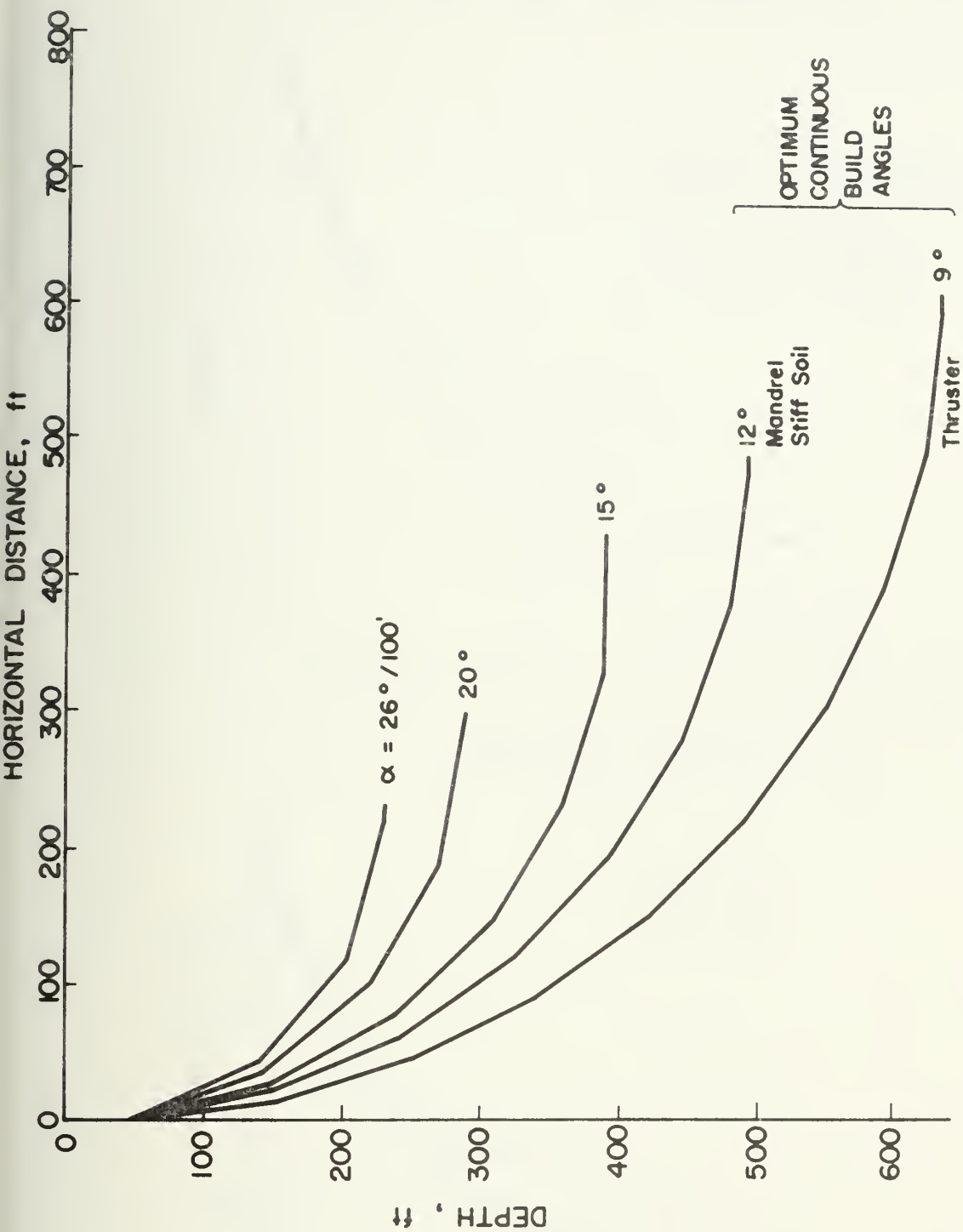FIGURE 3.27 Radius of Curvature vs. Object Diameter and Avoidance Distance

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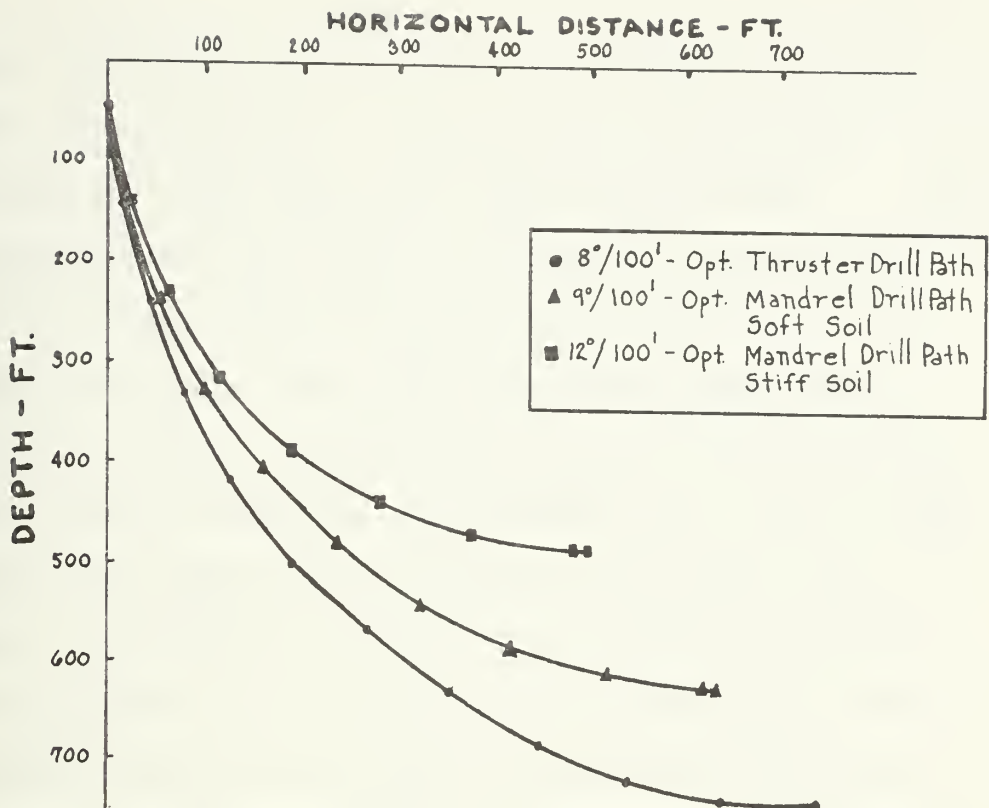FIGURE 3.28 Horizontal Distance vs. Depth for Various Build Angles

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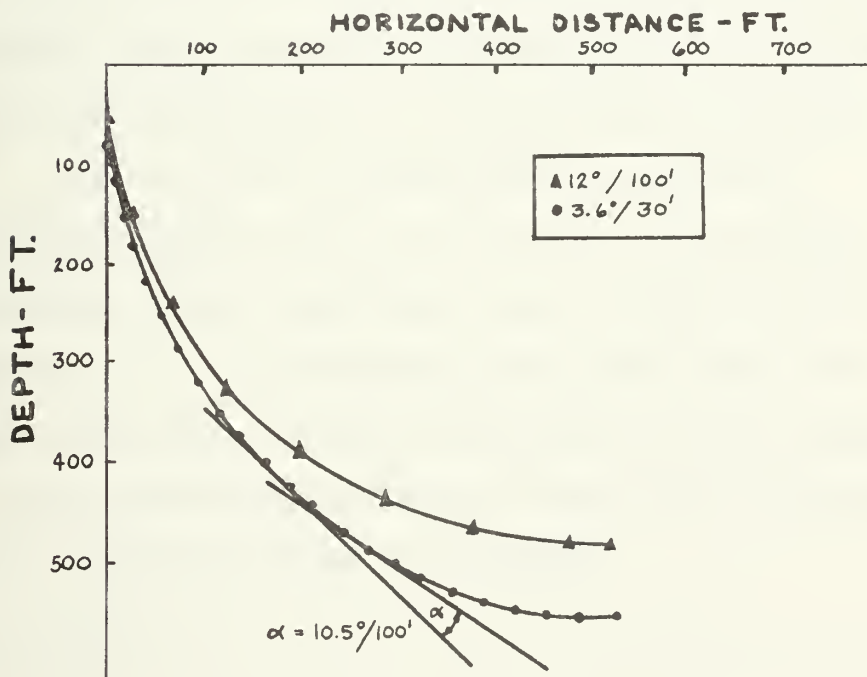FIGURE 3.29 Three Optimum Drilling Paths

FIGURE 3.30 Build Angle Comparison

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paths are drawn at 100 ft(31 m) increments between
angle change points. The difference between the
calculated drill paths for angle change rates
measured every 100 ft(31 m), which is the standard
interval, and those measured every 30 ft(9.2 m) are
shown in Figure 3.30. The calculated drill path
that is surveyed and plotted every 30 ft(9.2 m) falls
below the one measured and plotted every 100 ft(31 m)
while the actual build angle for the former drill
path is $10.5°/100'$ instead of the expected $12°/100'$.
The discrepancy is the result of assuming the chord
and arc length to be equal as discussed in the sub-
section "Drill Path Radius of Curvature." Therefore,
by decreasing the coarse length between measurement
points, a more accurate representation of the drill
path and capabilities of the MPS are represented.

A plot of the mathematical relationship
between constant radii of curvature, horizontal
distance, depth, and entry angle is illustrated in
Figure 3.31. By increasing the entry angle, the
depth required to reach a horizontal plane decreases
but the horizontal distance to that point increases
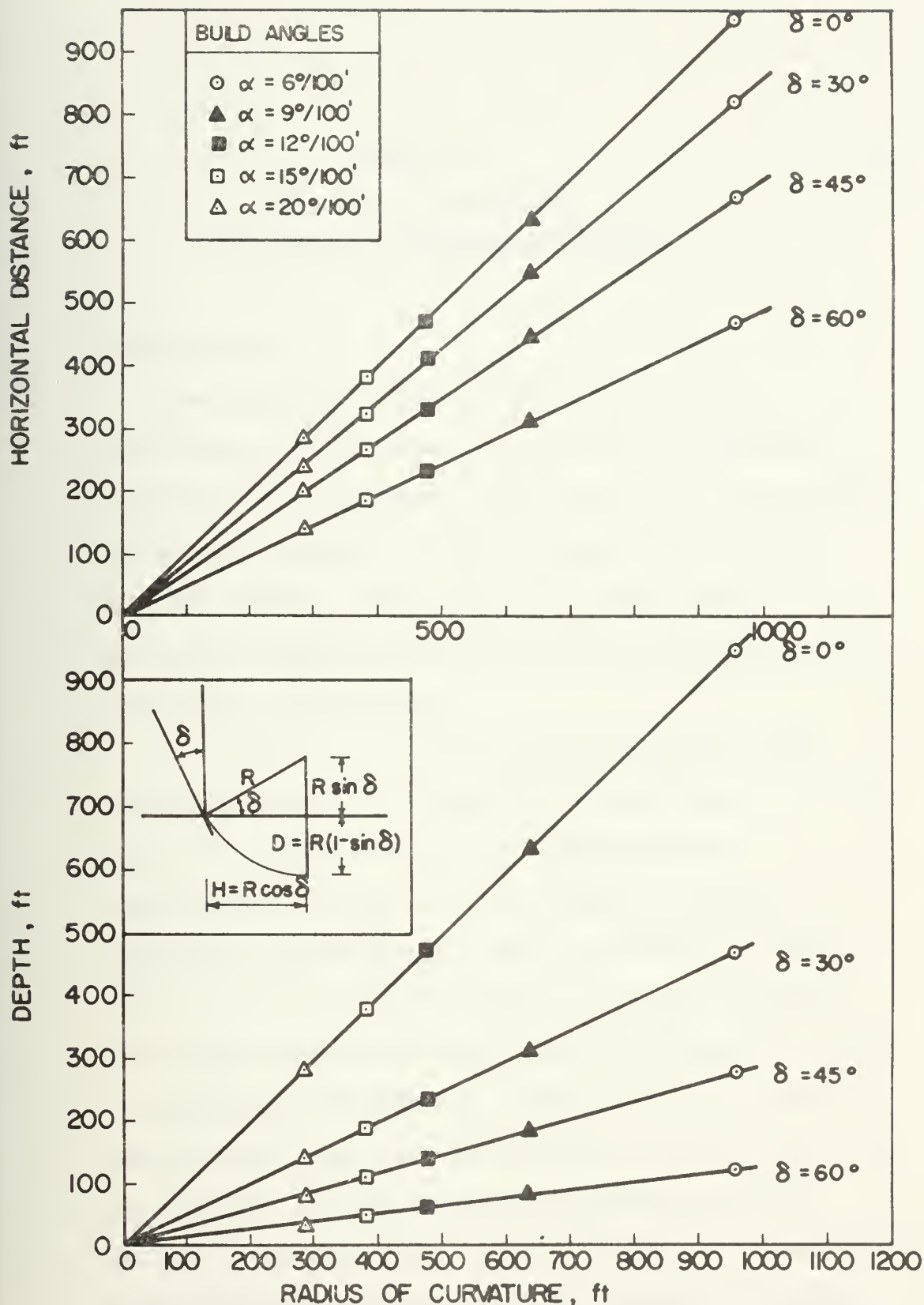for a constant radius of curvature.

FIGURE 3.31 Radius of Curvature vs. Horizontal Distance/
Depth for Various Entry Angles   139

CHAPTER 4

DESIGN OF A FEASIBLE
MANEUVERABLE PENETRATION SYSTEM

4.1   INTRODUCTION

Two aspects of horizontal directionally
controlled drilling have thus far been presented:
important soil-equipment considerations, and related
equipment necessary to directionally bore. With
this information, one should be able to select a
particular maneuverable penetration system(MPS) for
a specific drilling job.

In Chapter 1, several requirements for this
particular drilling system were established. At this
point it would be helpful to restate these
requirements. First, this MPS must be capable of
operating in soft ground down to a depth of 500 ft
(153 m) and drill horizontally for 5000 ft(1525 m).
Four basic geologies were chosen to represent a range
of operating environments. They were: (1) loose
sand or soft clay; (2) dense sand or stiff clay;
(3) residual soil with possible pinnacles; and
(4) any of the previous soil conditions in combination
with the presence of sub-surface man-made objects.

This chapter presents four MPS models which will be functional in at least one of the four geologies. First, the equipment which is presently available or currently being developed will be presented as feasible horizontal drilling equipment. Next, the process of selection will be discussed, including the logic and specific requirements associated with each geology. The four MPS designs resulting from this selection process will be presented and their characteristics discussed. The four MPS systems will then be compared with a dimensionless parameter analysis. The last section of the chapter contains two system compatibility schematics for the final equipment design for a mandrel and a thrust applicator MPS.

4.2   FEASIBLE EQUIPMENT FOR HORIZONTAL DRILLING

This section briefly presents equipment considered feasible for horizontal drilling in soft ground. A more detailed description of downhole motors can be found in Appendix C, while Appendix D elaborates on downhole thrusters. Due to the wide variation in available drill bits, specific manufacturers should be contacted. In addition, since there is only one deflection shoe device, one articulating sub, and one fixed angle bent sub available on the market, detailed drawings of the equipment can be obtained from the respective manufacturers mentioned

in Chapter 2 and whose addresses can be found in the
List of Contributors.

Downhole Motors   Three out of the four downhole
motors presented in the state of the art chapter are
considered feasible for drilling a horizontal hole in
soft ground. They are the Dyna-Drill, the W. H.
Nichols hydraulic pump motor, and the Century Electric
motor.

The Dyna-Drill is a well accepted and proven
mud hydraulic motor used in directional drilling, for
oil wells and river crossings. The W. H. Nichols
hydraulic motor and the Century Electric motor have
both been tested and proven acceptable in drilling
soft coal, therefore they should both be readily
adaptable for drilling in soft ground. The turbo-
drill was not considered a feasible soft ground
directional drilling motor because of its excessive
weight, lack of an indication that it has stalled
on the bottom of the hole, and the probable binding of
of the rotor and stator under a bending load induced
by a sharp turn in the drill path.

The Dyna-Drill can endure some bending induced
by sharp turns in the drill path (because of its
rubber stator), but not for any consistent operational
period. With time and excessive curvature, the
effects of bending a Dyna-Drill will lead to the

deterioration of the stator. A few of the problems associated with Dyna-Drill include the vibration resulting from the eccentric motor of the rotor. This vibration can aid the drilling process as well as interfere with the geophysical and navigational equipment that would be attached to the maneuverable penetration system. Another aspect which limits Dyna-Drill's application to the entire downhole drilling system is the extreme difficulty in connecting an electric cable to the up-hole, free end of the rotor. The seemingly insurmountable difficulty of threading a static, non-rotating wire through an eccentrically rotating shaft may eliminate the possible use of the bit module space (shown in Figure 4.3) with the Dyna-Drill. This module space can house geotechnical or geophysical sensing equipment as explained by Hedberg (1975). A later section will deal with available module spaces in the various proposed MPS's.

The W. H. Nichols hydraulic motor could be the most adaptable of the three downhole motors recommended for soft ground horizontal drilling. It is a relatively short motor (i.e. 4 ft(1.2 m) in length) and yet it still develops a very high torque output for a low flow rate. Shortness and low flow rates are optimal features for downhole motors.

In addition, this motor has a concentrically rotating shaft which allows electric sensing wires to pass through the motor to the previously mentioned bit module space. The concentric shaft and smooth operation of the gerotors reduce the external vibration.

Finally, the electric motor allows a reduction in the follower cable weight of the DRILCO thrust applicator by reducing the size of the slurry hose while still providing the same drillability characteristics of the two previously mentioned motors. However, the electric motor requires a reduction gear box between the motor and bit to reduce the bit RPM. A wire cannot be strung through the reduction gear box, therefore the forward bit module is inaccessible. Another minor problem with the elctric motor is its susceptibility to overloading and shorting out before corrective action could be taken by the drillers.

Even with the above mentioned related drawbacks with each motor, all of the recommended motors will perform in a soft ground environment and can be used for directionally controlled horizontal drilling.

Downhole Thrusters The only full sized operationally tested, downhole thruster presently available is the DRILCO thrust applicator. This thrust applicator has successfully drilled horizontal holes in soft coal

with a compressive strength about 1 tsf(95.7 kN/m^2).
Two other thrusters, the WORM and NURAT, have poten-
tial for application to soft ground drilling, however
they are still in the early development stages.

In order for the thrust applicator to operate
in soft ground it must be designed specifically for
that purpose. The 5-3/4 in(14.6 cm) O.D. model, in
its present configuration, can operate in very stiff
clay or compacted, cemented sands but not in soft
clay or loose sands. As previously mentioned in
Chapter 3, a possible redesign of the thruster pads
could improve the operation of the 5-3/4 in(14.6 cm)
O.D. thruster in clays.

The DRILCO thrust applicator cannot undergo
bending stresses for any extended period. Two prob-
lems are created in bending: (1) the piston rod will
bind within the cylinder section, and (2) the splime
within the cylinder section will wear excessively,
which increases the amount of precessing experienced
by the thruster.

The drilling system, WORM, has considerable
potential, if developed and satisfactorily tested.
The basic concepts and principles of operation appear
to make the system a feasible one for future applica-
tion to horizontal drilling. However, the manner in
which a device works on paper, as opposed to the field,

are two entirely different subjects.

Although least is known about the NURAT thruster, it too has the intuitive potential of being success- fully applied to horizontal drilling. The major problem to be resolved with NURAT is direction control.

From the above mentioned equipment, the downhole thruster which will be adopted for the final equip- ment design will be the DRILCO thrust applicator.

Direction Control All three of the direction control devices that were presented in the state of the art chapter are considered feasible for horizontal drilling in soft ground. They are the bent sub, the articulated bent sub, and the CONOCO deflection shoe.

The important question is, in what situation can these individual direction control devices be successfully applied? The bent sub with the fixed angle is most efficiently adapted to the mandrel system, since the thrust applicator system does not have a long drill pipe section which increases the amount of leverage (bending moment) applied to the bent sub. On the other hand, the deflection shoe is ideally suited for the thrust applicator system because of its self-contained ability to apply a lateral force to the bit. The deflection shoe might not have the same effectiveness when applied to the mandrel system because of the increased flexibility

of the equipment between reactive force locations.

The articulated sub is limited by its present
minimum diameter, 5 in(12.7 cm). Another limiting
factor is the requirement of a special locking probe
which will interfere with any survey system, except
the single shot magnetic method of navigation.

Drill Bits The three basic types of drill bits
available today and applicable to soft ground pene-
tration are the tricone roller, drag, and diamond
bits. Each of these bits is feasible for horizontal
drilling in soft ground and like the direction control
devices, each one has a specific application.

The tricone roller bit provides maximum cutting
ability with its deep cut, chisel shaped teeth, while
the roller bearings within each of the cones (as
shown in Figure 2.18) reduces the torque requirements
for cutting. The reduction in torque requirements
allows for the most efficient transfer of motor out-
put torque into shearing force at the outer edged
heel teeth. These heel teeth are responsible for
lateral excavation and thereby make the tricone the
most efficient directional drilling bit. However, a
major requirement for successful drilling is to keep
the deep cut teeth free from clogging with clay or
silty soil. Therefore, the drill fluid nozzle
design on the tricone bit becomes a critical item

for maintaining clean roller cone teeth without using too high of a stream velocity which would erode the bit face in soft ground. A further consideration when using a tricone bit is the maximum operational RPM. A general rule of thumb places an upper limit of approximately 500 RPM, which is not a hard and fast number, but instead the general consensus of the bit industry.

A major advantage of the cone roller bit design is the space that exists in the center of the bit, as shown in Figure 4.1 The bit shown here is a quadricone but is also available in a tricone version and is presently used as a coring bit. Smith Tool Company currently produces a 10-1/8 in(25.7 cm) O.D. with a 2-1/2 in(6.4 cm) core. However, with retooling, the smallest core bit they could produce would be a 7 in(17.8 cm) O.D. with a 2 in(5 cm) core (Gardner, 1974). The advantage gained by adopting this core bit design is the availability of the module space where the soil sample would normally be collected. A detailed explanation of the various geotechnical and geophysical instruments adaptable to this module space is found in Hedberg (1975).

The drag bit is an acceptable bit for drilling in soft ground. Because of the long outer edge of the cutting face (shown in Figure 2.18), the drag bit
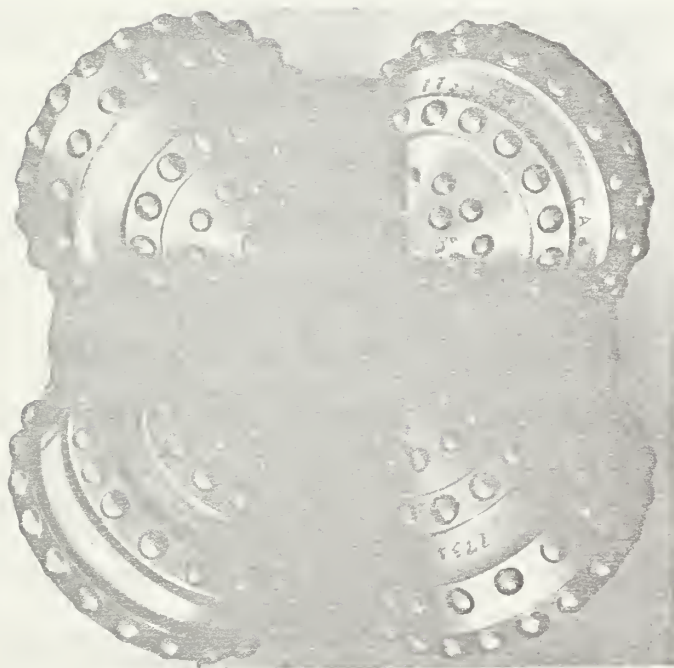
FIGURE 4.1 Coring Bit

requires more torque than a tricone to drill in the same formation. For this reason, the drag bit becomes inefficient beyond a particular size hole which is strictly a function of the bit-motor-combination and the type of formation being drilled. The shearing parameter, presented in a later section of this chapter, will help provide a means of analyzing this effect.

Finally, the diamond bit is successfully applied in drilling in soft ground when the bit RPM is in excess of 500 RPM and a residual soil condition is expected along the drill path. The diamond bit allows continuous drilling through residual soils for a longer distance than either a tricone or drag bit because it can penetrate core stones, whereas the drag bit cannot, and the tricone will wear rapidly unless fitted with tungsten carbide button inserts. Either one of the latter conditions will require the MPS to be pulled out of the hole to change bits, thereby increasing the overall drilling time.

4.3   SELECTION PROCESS

For each one of the geologies considered in the design process, there are certain requirements or characteristics which must be fulfilled by the MPS selected. Therefore, the selection process will be geared to finding a particular combination of the

previously mentioned feasible equipment which will
meet the following requirements.

The first condition considered is a loose sand
or soft clay environment. The MPS selected for this
type of subsurface soil condition must be a mechani-
cally simple device. This will eliminate the
possibility of in-hole mechanical failure because of
particle jamming (i.e. sand in the anchor pads).
The annular space available must also be sufficient
to maintain laminar flow as much as possible.
This will decrease the amount of particle settling
and decrease the amount of soil resistance and fluid
drag experienced by the MPS.

The next geological subsurface condition is a
dense sand or stiff clay environment. In this type
of subsurface soil condition, the MPS selected must
be able to overcome the possible increase in soil
resistance which would occur if the drill pipe or
hose drags along the horizontal section of the drill
hole. Here again, a sufficient annular size should
be maintained to allow for laminar flow of the
drilling fluid.

The third geological condition is a residual
soil environment. Any MPS selected for this environ-
ment must be able to handle the large distribution of
particle sizes one might encounter when drilling in a

residual soil. Therefore, the minimum size of the MPS is a very important parameter. In addition, the MPS must have the reserve torque available to bore through a large pinnacle and be able to drill in a medium stiff clay.

The final condition, an urban environment, is not directly related to geology but is more concerned with avoiding encountered utilities and other sub- surface objects. The subsurface soil conditions can be any one of the three previously mentioned environ- ments. Therefore, the most important consideration for selecting a MPS for this condition is the mechanical flexibility and maneuverability of the system.

Figure 4.2 presents the possible combinations of the equipment choices that have been discussed, in a decision tree format. The use of the decision tree format does not imply that a utility function analy- sis was performed to arrive at four final equipment design selections. As can be seen from Figure 4.2, there are several alternative solutions for an MPS that will meet the drilling requirements for a hori- zontal hole in a particular geology.
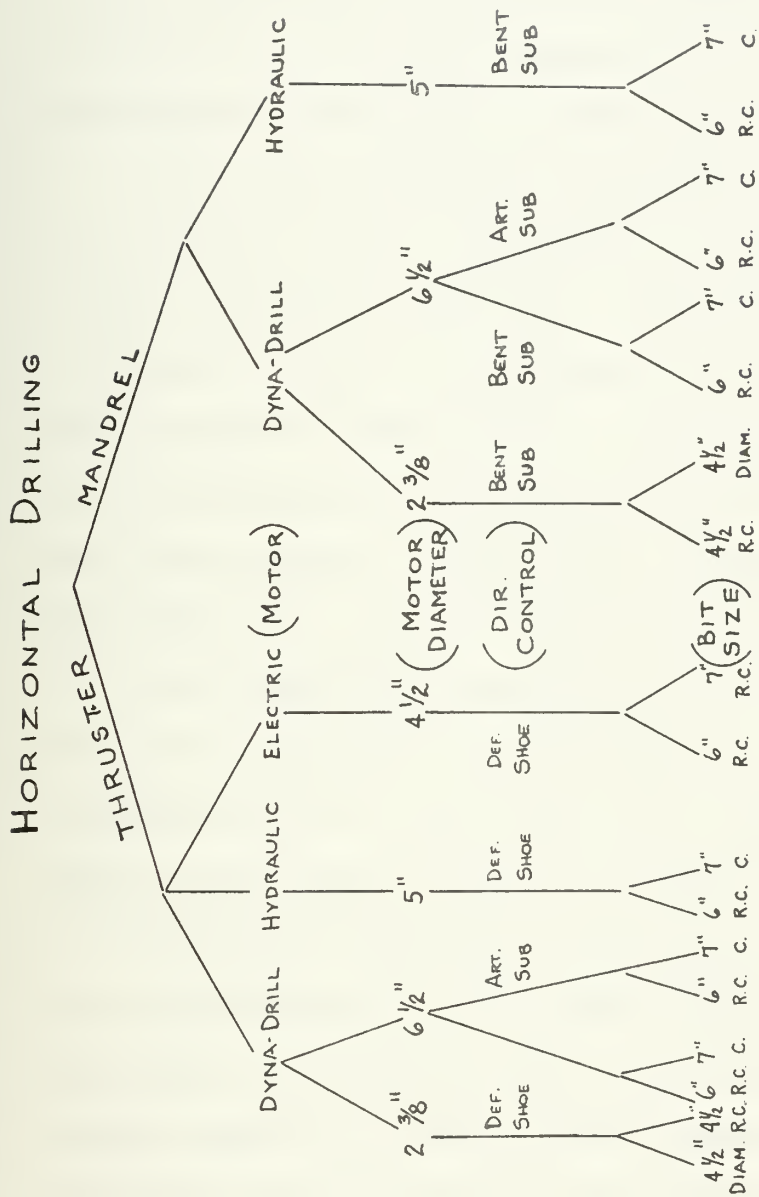
FIGURE 4.2 Horizontal Drilling Decision Tree

4.4   FINAL DESIGN SELECTIONS

The four final design selections are listed in
Table 4.1 Each one of these systems has been chosen
to not only meet the previously stated requirements
in Chapter 1, but also because of their applicability
to operate in more than one geological environment.

The first MPS listed, selection A, is the
2-3/8 in(5.4 cm) O.D. Dyna-Drill in combination with
a bent sub, 2-3/8 in(5.4 cm) diameter drill pipe, and
a diamond or drag bit (because of the high motor RPM).
This system is ideal for the soft clay-loose sand,
stiff clay-dense sand, and urban area condition.
The torque output is high while the flow rate is
relatively low, which is ideal for directional control.

The second MPS, selection B, is the 6-1/2 in
(16.5 cm) Dyna-Drill in combination with a bent or
articulated sub, 4-1/2 in(11.4 cm) diameter drill
pipe or an 8 in(20.3 cm) O.D. thrust applicator, and
a 12 in(30.5 cm) diameter tricone bit. This MPS
has been selected to be a heavy duty drilling system,
applicable to a residual soil with erratic pinnacles.
Another reason for such a large diameter system is to
allow for more geotechnical and geophysical equipment
space. Two normal force devices have been considered
with this motor because, if an 8 in(20.3 cm) O.D.
thruster is designed specially for soft ground

Table 4.1 Final Design Selections

Selec'n	A	B	C	D
Drill Motor	Dyna-Drill	Dyna-Drill	Nichols Hyd. Motor	Century Electric Motor
Drill Motor O.D. (in)	2-3/8	6-1/2	5	3-11/16
Length (ft)	7	19.6	4	4.5
Normal Force Device (NFD)	Drill Pipe	Thrust Appl. / Drill Pipe	Thrust Appl.	Thrust Appl.
NFD O.D. (in)	2-3/8	8(T.A.) / 4-1/2 (D.P.)	5-3/4 or 8	5-3/4 or 8
Direction Control	Bent Sub	Def.Shoe (T.A.) / Bent Sub (D.P.)	Def. Shoe	Def. Shoe
Bit Type	Diamond or Drag	Tricone	Tricone	Tricone
Hole Dia. (in)	4-1/2	12	7	7
Comments	Excellent annulus size low flow rate, high torque	Max. annular size, max. torque RPM, high flow rate can be a problem	Opt. annular space, short length high torque low flow	Opt. annular space, min. flow requirements, short length, problem w/shorting

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conditions, then a thrust applicator could be used in soft clay soils that might also contain random boulders or pinnacles.

The next MPS, selection C, is the 5 in(12.7 cm) O.D. W. H. Nichols hydraulic motor in combination with a modified 5-3/4 in(14.6 cm) O.D. or redesigned 8 in(20.3 cm) O.D. thrust applicator, deflection shoe, and tricone core bit. This MPS can easily operate in a stiff clay or dense sand formation; however, as previously stated, a redesign of the thrust applicator is required for operation in soft clay.

The final MPS, selection D, is the Century Electric motor in combination with either the 5-3/4 in (14.6 cm) or the proposed redesigned 8 in(20.3 cm) O.D. thrust applicator, deflection shoe, and a 7 in (17.8 cm) diameter tricone core bit. This MPS can operate in the same geological conditions as selection C but has the added ability of operating with all of its components being electrical (except for the CONOCO deflection shoe). This allows the drilling mud slurry to be employed strictly to clean the bit and stabilize the hole.

In fact, what might be possible with the electric motor-thrust applicator MPS is to maintain just enough pressure at the bit to clean the drill

bit teeth. The drilling fines would be carried past
the thrust applicator and allowed to settle out
around the thruster cable. Therefore, there would
be no need to recirculate the drilling fluid and the
device would operate without cleaning out the drill
hole. The biggest advantage to this would be the
elimination of a drilling fluid recirculation system.
However, the biggest disadvantage would be the reduc-
tion in travel distance due to an increase in the
frictional resistance at the soil-hose interface.
The actual calculations of this frictional effect
have not been computed, however in this case, a
neutrally buoyant thruster hose would be very bene-
ficial to reduce frictional forces acting on the
hose. The flow rate for the drilling fluid would be
just enough to cool the electric motor, clean the bit
and fill the hole with a very viscous mixture of
drilling slurry and fines.

Table 4.2 summarizes the MPS-geology
compatibility relationship as related to the four
final design selections.

Throughout this chapter, reference has been
made to certain module spaces available with each MPS.
One objective of the design method was to isolate
certain spaces on each MPS which could be adapted for

Table 4.2 MPS-Geology Compatibility

	Loose Sand Soft Clay	Dense Sand Stiff Clay	Residual Soil	Urban Environment
2-3/8 in O.D. Dyna-Drill with 2-3/8 in drill pipe	Yes^o	Yes	Yes$^\Delta$	Yes
6-1/2 in O.D. Dyna-Drill with 4-1/2 in drill pipe	No$^+$	Yes	Yes	No
5 in O.D. Nichols Hyd. Motor with 5-3/4 in O.D. DRILCO Thrust Applicator	Yes*	Yes	No	Yes
3-11/16 in O.D. Century Electric Motor with 5 in O.D. casing and 5-3/4 in O.D. DRILCO Thrust Applicator	Yes*	Yes	No	Yes

Remarks: Δ - With Diamond Bit

o - Must use Washover Pipe

* - Thrust Applicator Requires Redesign

+ - Due to Excessive Weight, See Appendix C

additional geotechnical or geophysical instru-
mentation. Figure 4.3 identifies the specific areas
on the thrust applicator MPS designated as module
spaces. The thrust applicator has the following
module spaces: (1) core of tricone coring bit,
(2) bit sub, (3) deflection shoe pad, (4) anchor pads,
(5) additional equipment packages between the orienta-
ting motor and drill motor, and (6) follower packages
behind the thrust applicator. The mandrel MPS has the
following module spaces: (1) bit sub, (2) area on the
Dyna-Drill motor around the internal connecting joint,
and (3) within the drill pipe.

4.5   DIMENSIONLESS ANALYSIS

Four parameters, described in Appendix E, will
be used to compare the performance of the four
design selections. Three of the four parameters are
dimensionless while the fourth is a ratio whose units
are meaningless. The four parameters are the shear-
ing, jetting, drill motor, and fluid system
parameters.

The shearing parameter relates the undrained
shear strength of the soil to the maximum rated
torque of the drill motor. The jetting parameter is
the ratio of the velocity necessary to erode soil
divided by the drilling fluid velocity at the bit

orifice. The fluid system parameter is the equivalent circulating density of the drilling fluid, divided by the hydraulic fracture gradient of the soil. Finally, the drill motor parameter is the dimensional parameter that relates the output horse-power of the motor in relation to the volume of the motor to the rated output torque of that motor.

Table 4.3 summarizes all of the calculations for estimating the four parameters. Also included on this table is the most favorable condition or value for each particular parameter. Briefly, the logic behind the "most favorable conditions" is as follows (more details are presented in Appendix E): A shearing parameter greater than 1.0 indicates the motor will have difficulty drilling, if shearing at the outer edge of the bit is the predominant cutting mechanism for that particular bit (i.e. drag bit). Therefore, a drill bit with less of a torque require-ment (i.e. tricone bit) should be used with that particular motor. Any value less than 1.0 should provide good torque transfer efficiency for either one of the suggested drill bits. The larger the value of the jetting parameter the less erosion will occur in front of the bits, therefore the less chance there is of creating a large cavity at the drill face when the equipment advances slowly. The drill motor

Table 4.3 MPS Comparison Parameters

	Shearing Parameter (SP)		Jetting Parameter (JP)		Drill Motor Parameter (DMP)	Fluid System Parameter (FSP) Clay		Sand	
	S_n=0.25 tsf	2.0	Sand	Clay		100 ft	500 ft	100 ft	500 ft
2-3/8 in D-D (4-1/2 in hole)	0.173	1.38	0.094	0.045	1018.5	0.76	0.91	0.81	0.97
6-1/2 in D-D (12 in hole)	0.210	1.68	0.029	0.014	14.6	0.73	0.88	0.78	0.94
Hydraulic Motor (7 in hole)	0.111	0.89	0.132	0.063	39.8	0.73	0.89	0.78	0.95
Electric Motor (7 in hole)	0.111	0.89	0.132	0.063	78.6	–	–	–	–
Most Favorable Condition	1.0 or less		larger value		smaller value	smaller value			
Formula	$SP=\dfrac{S_u\left(\dfrac{d^3}{16}\right)}{T}$		$JP=\dfrac{V_e(448)}{\dfrac{GPM}{A_{BO}}}$		$DMP=\dfrac{HP(550)}{\dfrac{Vol}{T}}$	$FSP=\dfrac{ECD}{HFG}$			

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parameter is an indication of the maximum design efficiency of the drill motor. The smaller the ratio value, the more efficient the motor. The smaller number means that a high torque output is accomplished with a minimum amount of rated power for a given size hole. Finally, the fluid system parameter should be less than 1.0 because any number greater than 1.0 means the annular pressure is greater than the minor principle stress in the hole, resulting in hydraulic fracturing of the soil.

The results from this analysis can be interpreted in the following manner. The hydraulic motor and electric motor, have the lowest shearing parameter for both soil strengths. Therefore, the rated torque output can easily shear the soil if that were the only mode of drilling the hole. The two values greater than 1.0 for the Dyna-Drill motor indicate that because of a lower rated torque output, drill bits which abrade rather than shear will have to be used.

The jetting parameter values indicate the hydraulic and electric motor both have a minimum jetting velocity, therefore, they will create the least amount of soil erosion at the bit face. Since the 6-1/2 in(16.5 cm) O.D. Dyna-Drill has the highest flow rate, it is intuitively obvious that this drill

motor will have the greatest erosive effect at the bit face.

However, when the drill motor parameter is considered, the larger Dyna-Drill appears to have the most efficient usage of its volume and power rating to produce a specific amount of torque. This then is one of the reasons for selecting it to be the heavy-duty drill motor. It is interesting to note that the small diameter Dyna-Drill has a very high drill motor parameter, however this is indirectly related to a low flow rate design which attempts to minimize the erosive jetting effects.

Finally, the fluid system parameter indicates that all of the systems considered for the final design have sufficient annular space such that hydraulic fracturing should not occur in fully satu-rated sand or clay because of excessively high annular fluid pressures at the bit.

In summary, the development of these parameters has required the author to analytically compare each MPS rather than subjectively stating that the four final designs will perform within a specific formation. The parameters presented are tools which should be used to objectively decide which drilling system is most compatible with a particular formation.

4.6   DESIGN COMPATIBILITY DRAWING

Figure 4.3 is a scaled drawing of the basic thrust applicator MPS with the equipment recommended from the previous section. This drawing is not intended to be a working drawing, but instead, is to illustrate the size compatibility of the various subsystem components. No intent has been made to duplicate manufacturers' drawings.
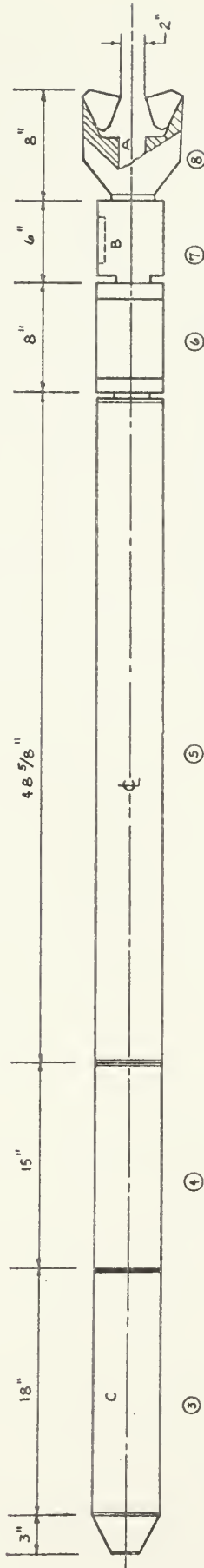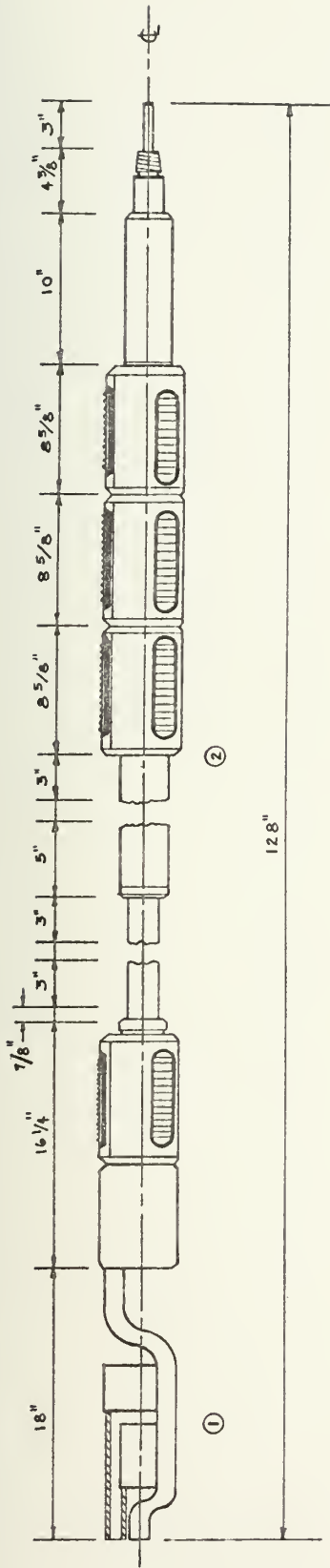
FIGURE 4.3 - THRUST APPLICATOR MPS

COMPONENTS		DETAILS		MODULE SPACES
①	DOWNHOLE HYD VALVING	APP. D	A	BIT MODULE
②	THRUST APPLICATOR	SEC 2.3, 4.4, APP. D	B	BIT SUB MODULE
③	ELECTRONIC PACKAGE		C	COMPONENT PACKAGE
④	ORIENTATING MOTOR	SEC. 2.4		
⑤	HYD DRILL MOTOR	SEC. 2.2, 4.4, APP. C		
⑥	DEFLECTION SHOE	SEC. 2.4, 3.3		
⑦	BIT SUB	SEC. 2.4, 3.3		
⑧	TRICONE CORE BIT	SEC. 4.4		

SCALE: 1/8"

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